Depositional Environments and Sequence Stratigraphy of the Lower Cretaceous Dakota Sandstone in the Ridgway Area, Southwestern Colorado

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Acknowledgments

I would like to dedicate this thesis in memory of my grandfather, who always believed in me. I would also like to dedicate it to my parents (Hamid and Samia), my brother (Djallel) and to my sister (Tiha). Thank you for your love and support.

I am especially grateful to my advisor Dr. Diane Kamola for her help, patience and her unlimited support. Diane, thank you for choosing me to be part of this program. Thank you for helping me choose this thesis and helping me along these two years.

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Abstract

The Dakota Sandstone records the initial transgression of the Cretaceous western interior seaway across southwestern Colorado. This transgression does not show a simple pattern. The sequence stratigraphic analysis of the Dakota Sandstone indicates that the initial part of this transgression occurred in multiple steps.

This study concentrates on eleven sections in the Ridgway, Colorado area. Facies analysis identified five depositional facies: delta plain, delta front, radial bifurcating channel (distributary-channel), lower shoreface and fluvial channel. Deltaic facies are the predominant facies and show interaction between fluvial and marine processes. Higher wave influence is present in the upper part of the formation, seen by the presence of hummocky cross stratification in a lower shoreface setting. This increase in wave energy suggests a change in shoreline configuration. At the base of the formation, deltaic sediment accumulated in an embayed coastline, protected from wave energy. Near the top of the formation, the shoreline became straighter with higher wave influence. At the top of the formation, the shoreline returned to an embayed configuration.

Sequence stratigraphic interpretation of the Dakota Sandstone reveals the presence of eleven parasequences and three depositional sequences, with two incised valleys. Sequences are bounded by erosional surfaces or their correlative interfluve expressions. Sequence one starts in the underlying Burro Canyon Formation, continues into the Dakota Sandstone, and includes seven parasequences represented by delta plain, delta front and distributary channel facies. These parasequences show

a retrogradational followed by an aggradational stacking pattern. Sequence two contains three parasequences and includes an incised valley-fill at the base overlain by lower shoreface and delta-front facies. The staking pattern is defined as aggradational within this sequence. The lower part of sequence three occurs within the Dakota Sandstone; the remainder of the sequence occurs in the overlying Mancos Shale. The part of sequence three within the Dakota Sandstone is represented entirely by fluvial deposits within an incised valley.

The sequence stratigraphic interpretation of the Dakota Sandstone in southwestern Colorado reveals the complexities related to the initial transgression of the Cretaceous Western Interior Seaway. These complexities are seen via the presence of different sequences, as opposed to a single parasequence set characterized by a retrogradational stacking pattern.

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Chapter I: Introduction

I. Purpose of Study

By the mid-Cretaceous, the Cretaceous western interior seaway (KWIS) stretched from central Utah to the western Appalachians, and from the Arctic to the Gulf of Mexico (Blakey and Umhoefer, 2003). Many studies have focused on the causes and the consequences of this transgression (Blakey and Umhoefer, 2003; McGooker et al., 1972; Ulicny, 1999; Valdes, 1993; Gustason, 1985), however, to date, there are few detailed studies about the nature and the characteristics of the transgression itself. The Lower Cretaceous Dakota Sandstone records the initial transgression of the Cretaceous seaway across southwestern Colorado. A detailed study of this formation is key to understanding the nature of this transgression. The purpose of this study is to reveal the nature of the initial phase of the transgression of the KWIS, as studied in the Ridgway, Colorado area. This study uses a detailed facies and sequence stratigraphic approach to investigate whether the transgression occurred as one continuous event or as different, distinct steps with a more complicated history. In this way, the strata are analyzed to understand the fluctuations in the relative position of the sea level of the Cretaceous seaway during the time of deposition of the Dakota Sandstone. The complexity of the sequence stratigraphic interpretation will reflect the complexity of the transgression during this time.

II. Stratigraphy and Paleogeography

The study is conducted in southwestern Colorado, near the town of Ridgway (Ouray County; fig 1). The study area extends approximately 22 km (from north to south). Although the Dakota Sandstone is well exposed in the area, there are no published detailed studies describing its depositional environments or sequence stratigraphy.

The stratigraphic nomenclature used to describe the Dakota Sandstone is complicated (fig 2). The unit now known as the Dakota Sandstone has been identified by various other names. Meek and Hayden (1861) first named this unit "The Dakota" near the town of Dakota (northeastern Nebraska). Later, many authors used variations of the name: Dakota Formation, Dakota Group, Naturita Formation, Dakota Sandstone (Bartleson, 1994; Burbank, 1930; Carter, 1957; Gustason, 1989; Meek and Hayden, 1861; Weimer, 1982; Young, 1960). In this paper, the term Dakota Sandstone will be used to describe this formation in the Ridgway area. The Dakota Sandstone represents a transgressive event in western Colorado (Young, 1960). Because of the controversies related to its stratigraphy, and the lack of detailed studies, the exact age of the formation is unknown in the Ridgway area, but is estimated to be Early Cretaceous (Weimer, 1982) (fig 2). The Dakota Sandstone is underlain by the Lower Cretaceous Burro Canyon Formation, and overlain by the Mancos Shale (Young, 1960). The Mancos Shale is considered to be Late Cretaceous (Young, 1960). It consists of organic-rich black shale deposited in very low oxygen conditions (Weimer, 1982).

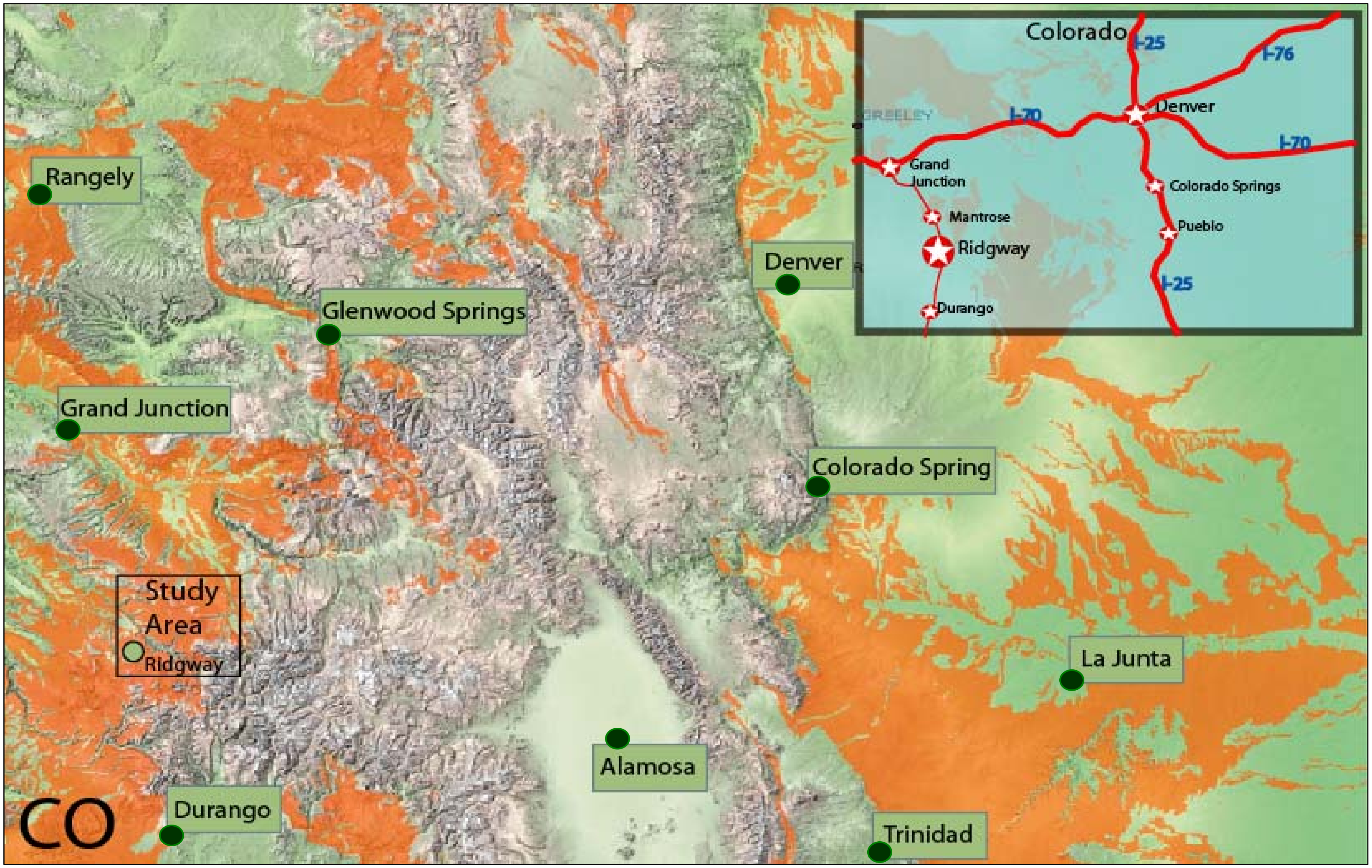

Fig 1: Map of Colorado showing the study area (Ridgway). The distribution of the Cretaceous rocks is shown by the orange color. Modified from http://geosurvey.state.co.us/Default.aspx?tabid=417 (Sept, 2007).

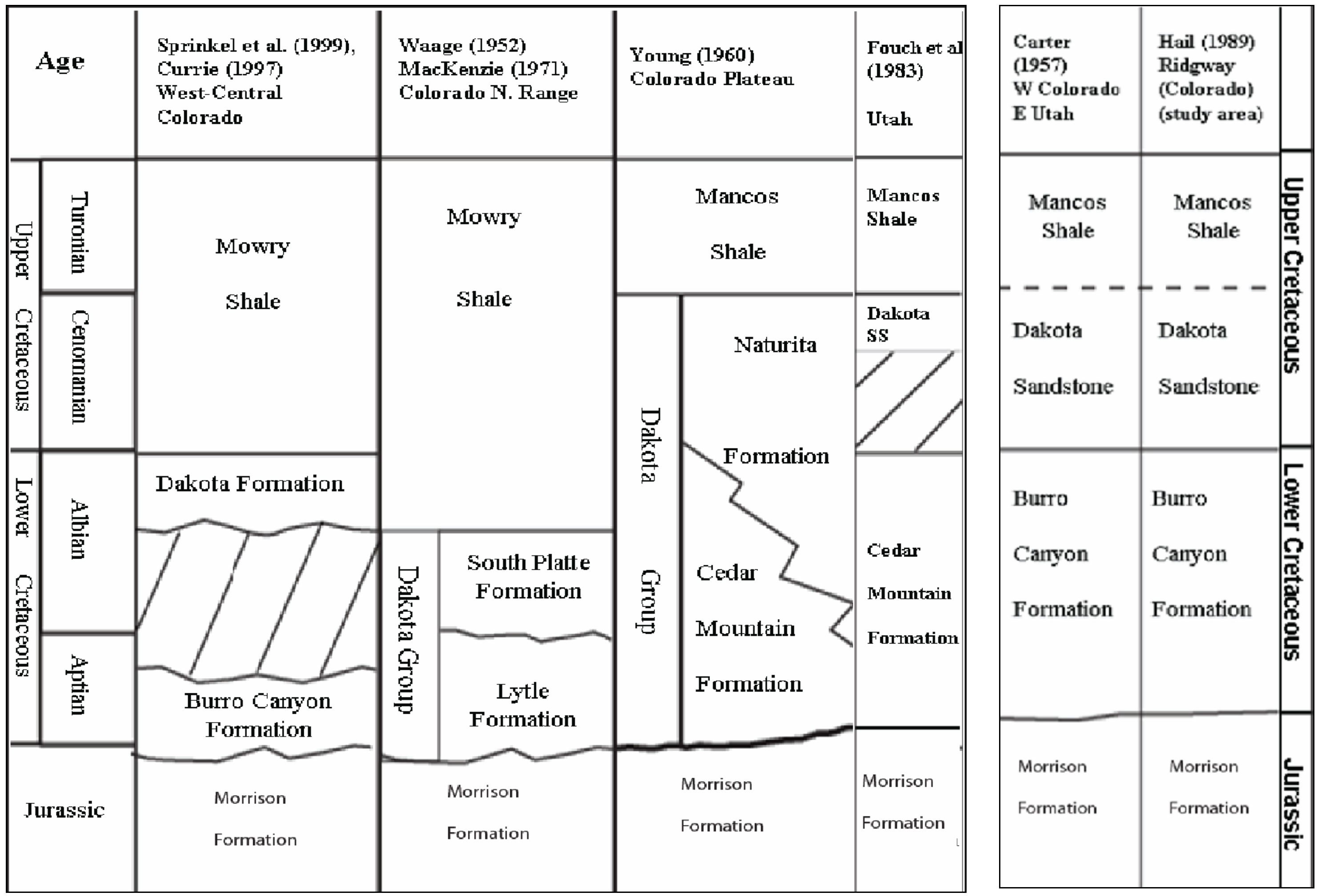

Fig 2: Chart showing the complexity in the nomenclature of the Dakota Sandstone in the study area and surrounding localities. Compiled from Carter (1957), Currie (1997), Fouch et al. (1983), Hail (1989), McKenzie (1971), Sprinkel and others (1999), Waage (1955) and Young (1960).

The Mancos Shale represents the offshore and open sea environment of the Cretaceous Western Interior Seaway (Weimer, 1982).

During the Cretaceous, marine waters flooded across the North American continent simultaneously from the Arctic and the Tethys regions. These epicontinental seas joined in Colorado to form the Cretaceous western interior seaway (fig 3 and 4). The study area lies at the western part of the KWIS, approximately 400 km east of the thrust front of the Sevier Orogenic belt. The Cretaceous Western Interior foreland basin occurs along the western margin of the KWIS. The location of the paleoshoreline during the deposition of the Dakota Sandstone is not well defined in the study area.

III. Methods

This study is an outcrop investigation. The Dakota Sandstone is studied at eleven measured sections between the towns of Montrose and Ridgway (fig 5). Nine of the sections form a N-S line approximately 22 km long. Sections range from 26 to 32 m in thickness and were measured using a Jacob’s staff. Sedimentological observations include description of lithology, physical and biogenic sedimentary structures, and bedding attributes such as bed thickness, bedding contacts, etc. Attention was paid to the recognition of major bounding surfaces formed in response to base level changes (i.e., parasequence and sequence boundaries).

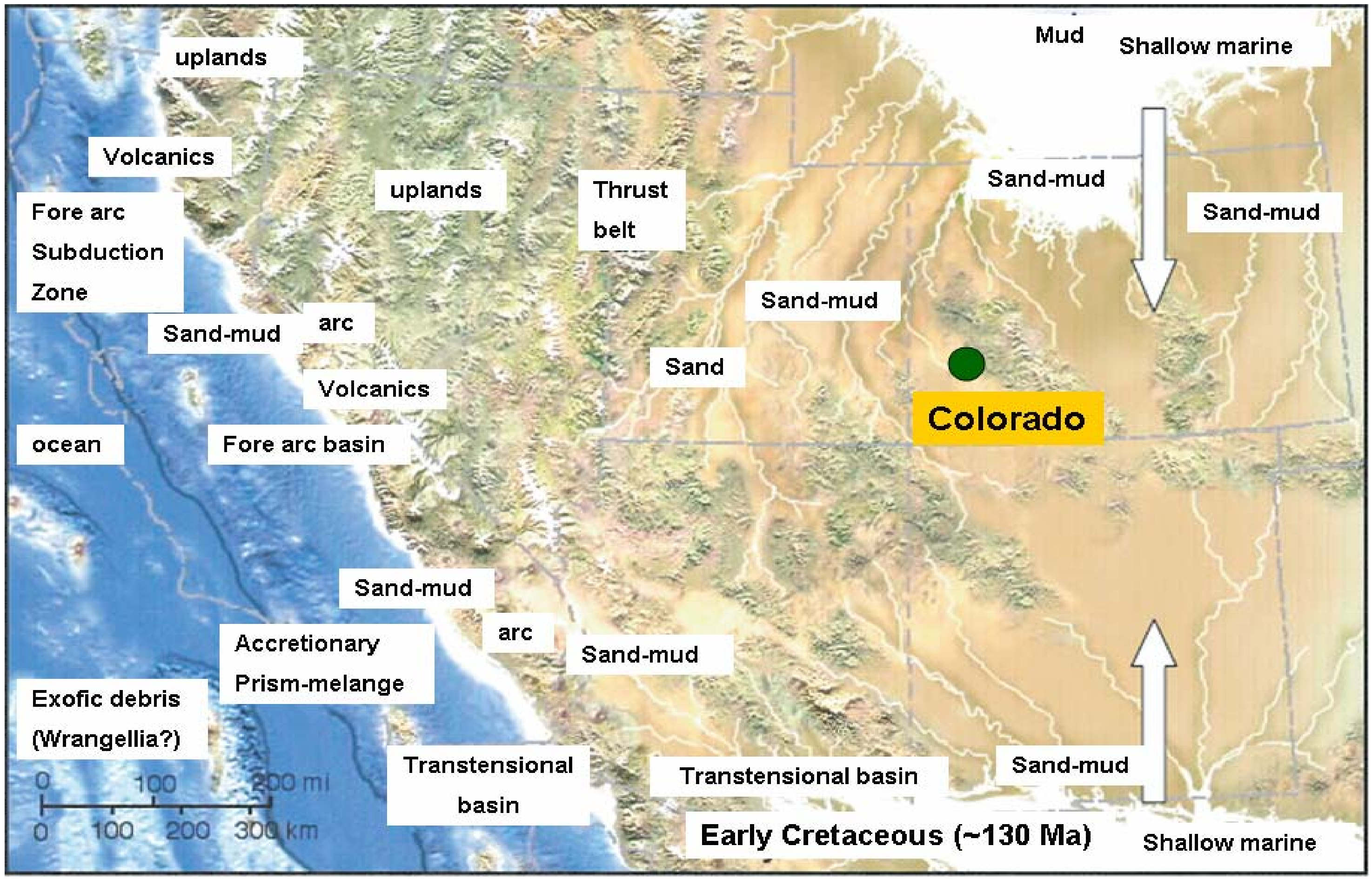

Fig 3: Paleogeography of the western United States during the Early Cretaceous (130Ma) showing the northern and southern transgression of the KWIS (in white). The arrows show the movement of the flooding events. The green circle represents the location of the study area. Modified from an image downloaded from http://jan.ucc.nau.edu/~rcb7/crepaleo.html (Sept, 2007).

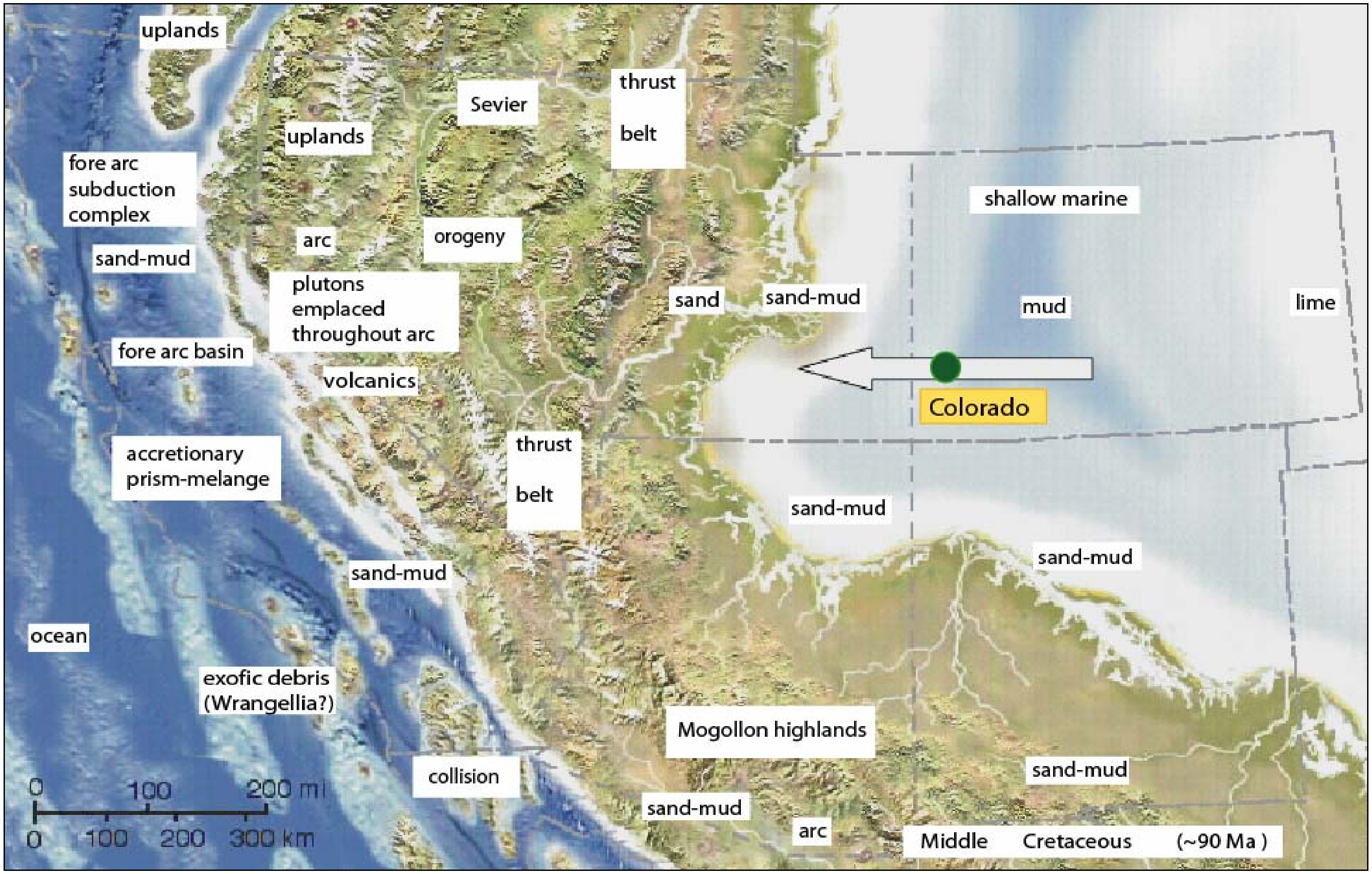

Fig 4: Paleogeography of the western United States during the Mid Cretaceous (90Ma) showing the extent of the KWIS (in white). The arrows show the movement of the Cretaceous seaway. The green circle represents the location of the study area. Modified from an image downloaded from http://jan.ucc.nau.edu/~rcb7/crepaleo.html (Sept, 2007).

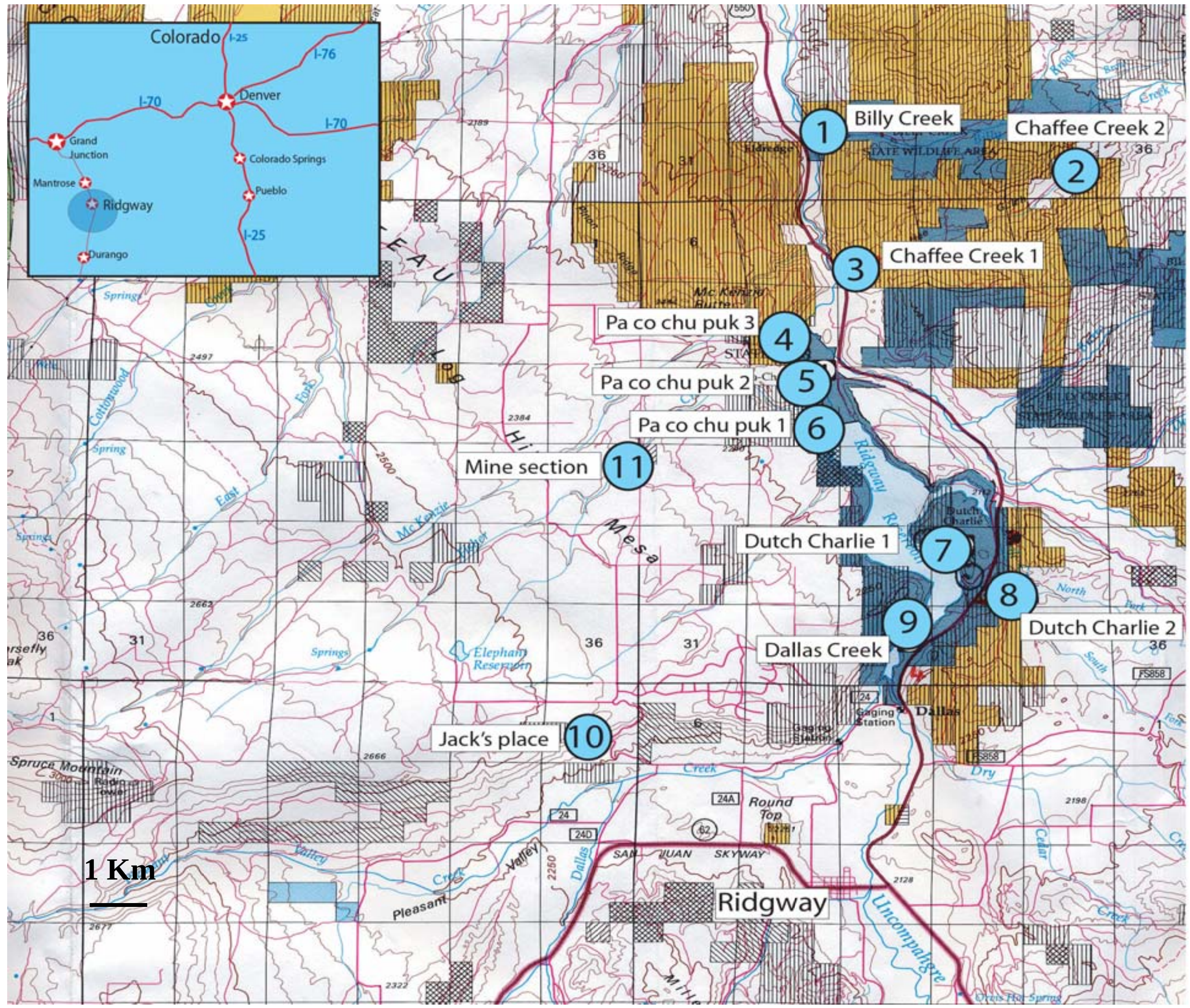

Fig 5: Map of the Ridgway area showing the eleven measured sections. Yellow areas on this map indicate public lands and monuments. Blue areas represent state, country and outdoor recreation areas.

Photo mosaics were taken to help determine the architecture of beds and bed sets.

Correlation of measured sections using a sequence stratigraphic approach documents lateral facies changes, as well as the connectivity (or lack of) of the sandstones within this formation. Individual parasequences and their stacking pattern reveal the nature of the mid-Cretaceous transgression and document its complexity.

Chapter II: Facies description, interpretation and correlation

I. Facies description and interpretation

Outcrop investigation of the Dakota Sandstone allows for the identification of six facies (table 1) that are interpreted as delta-plain (A), delta-front (B), radial bifurcating channel (distributary-channel) (C), lower shoreface (D), sinuous fluvial channel (E), and high-energy fluvial channel (F).

Deltaic environments are characterized by a number of subenvironments. Reading (1996) divided the delta system into delta-plain, delta-front and prodelta settings (fig 6). The delta-plain is a subaerial zone dominated by rivers and associated floodplain, crevasse splay and lake deposits. It also includes interdistributary environments such as swamps, marshes and bays. The delta-front occurs seaward of the delta-plain and is a zone of interaction between fluvial and basinal processes. It is subdivided into proximal delta-front (closer to the river) and distal delta-front (closer to the basin). These two parts of the delta-front differ in the sand/silt ratio, sedimentary structures and the diversity of burrows. The prodelta is a marine zone where sedimentation occurs from suspension. The prodelta includes slump and sediment gravity flow deposits. The terms delta-plain, delta-front and prodelta are used throughout this thesis.

One bentonite bed (fig 7, 8) is describe in the study area. This bed (up to 25 cm thick) is present in only 4 sections (Billy Creek, Chaffee Creek 1,

Pa Co Chu Puk 3 and Dallas Creek), in the upper half of the Dakota sandstone Formation.

Facies (thickness)	Lithologic characteristics	Interpretation
A (1 to 5 m)	Dark gray silty shale, locally carbonaceous, sporadically interbedded with 10 to 50 cm thick beds of quartz arenite with sharp base, current ripple lamina and cross beds.	Delta plain
B (1.5 to 7 m)	Upward-coarsening succession; laminated gray silty shale interbedded with cm scale sandstone beds at the base, to medium-upper grained quartz arenite (locally carboneceous) at the top. Current/ wave modified current ripple lamina alternate with planar bedding at the top of the unit.	Delta front
C (1.5 to 3 m)	Sharp-based, medium-grained quartz arenite with rip-up clasts or carbonaceous-rich lag at the base overlain by planar tabular or trough cross beds.	Radial, bifurcating distributary channel
D (2.5 to 3 m)	Fine-grained, well-sorted, quartz arenite dominated by HCS.	Lower shoreface
E (~ 6 m)	Sharp-based, upward-fining succession ranging from medium-upper sandstone at the base to alternating silt and fine sandstone at the top. Rip-up clasts and compound cross stratification at the base are overlain by current ripple lamina and low-angle cross beds, which are overlain by planar bedding with wave-modified current-ripple lamina at the top. Lateral accretion present.	Sinuous fluvial channel
F (~7 m)	Scour base, upward-thinning beds of medium-upper quartz arenite with abundant planar tabular cross beds. Wave-modified current-ripple lamina at the top of the facies.	High-energy fluvial channel

Table 1: Summary of the facies present within the Dakota Sandstone in the Ridgway area.

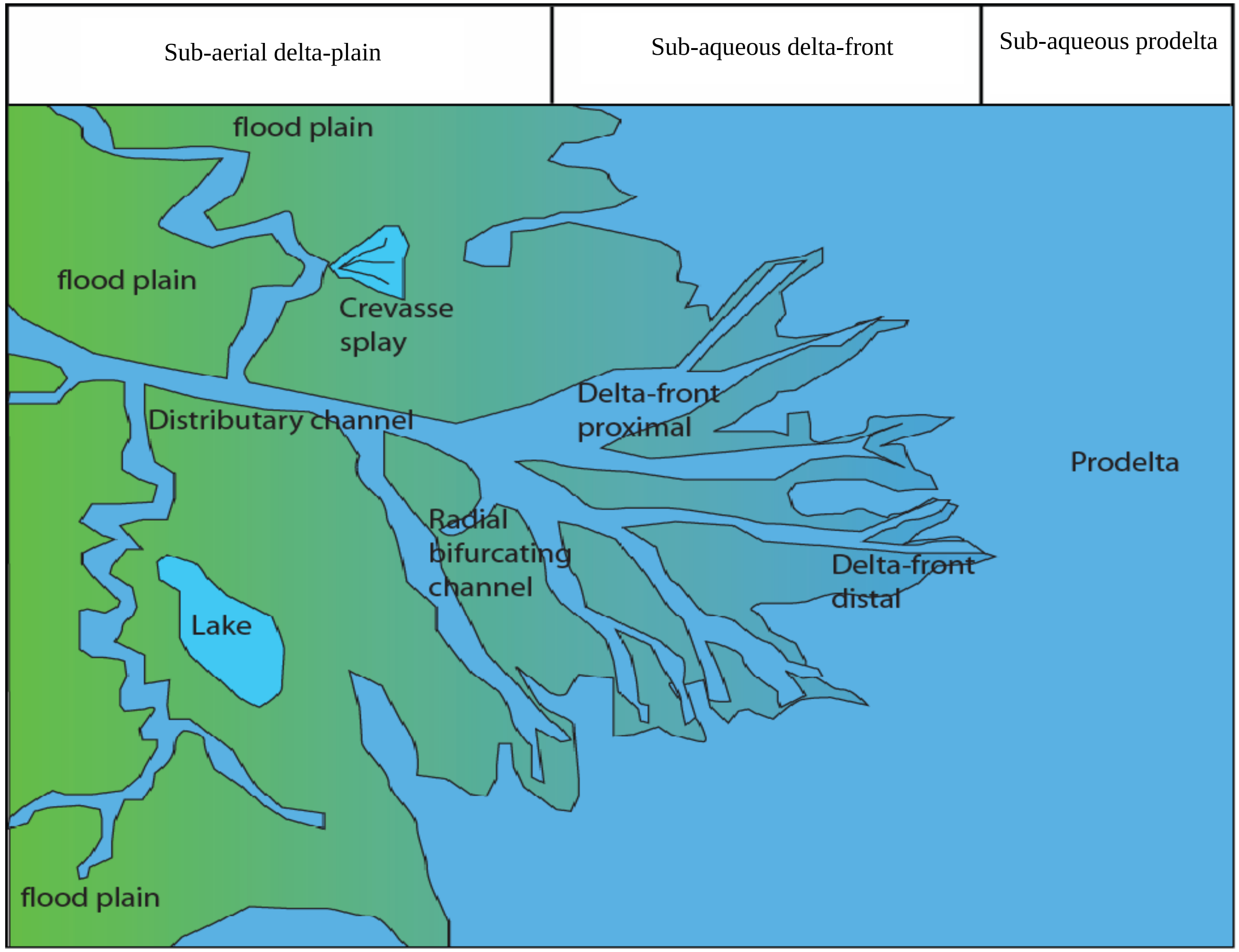

Fig 6: Different components of a deltaic system.

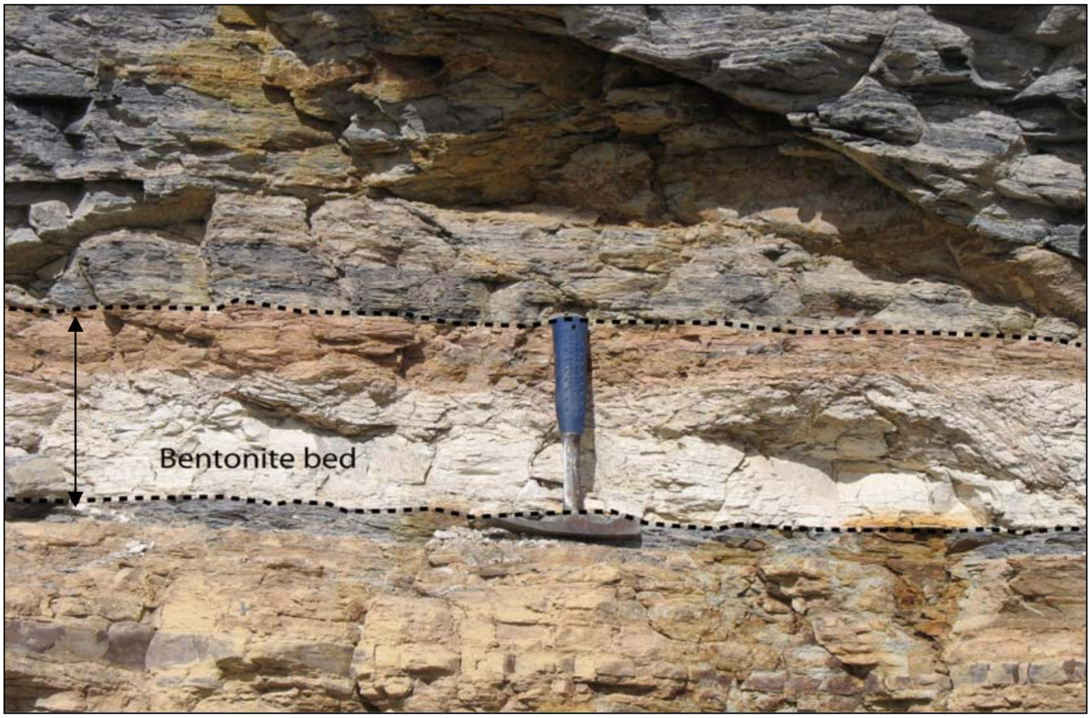

Fig 7, 8: Bentonite bed delimited by the arrows in measured sections localities Dallas Creek and Pa Co Chu Puk 3. The contact between the Bentonite and the overlain facies is gradational. The rock hammer is 25 cm long. The Jacob staff is 1.5 m long.

Within the Dakota Sandstone, the bentonite bed provides an excellent and widespread time marker. The bentonite cross cuts facies lines and indicates an isochronous surface of deposition.

A. Facies A description

Facies A is dominated by dark gray silty shale (locally carbonaceous), sporadically interbedded with 10 to 50 cm thick beds of quartz arenite (fig 9). In one section (Billy Creek), a coal bed up to 10 cm thick tops this facies (fig 10). Facies A ranges in thickness from 1 to 5 m. It is present at the base of the Dakota Sandstone and extends laterally along all the sections (22 Km). Because of the crumbly nature of the silty shale, this facies is poorly exposed (fig 11). Sandstones (locally carbonaceous) are not well exposed. Where the lower contact of the sandstone is exposed, it is characterized by a scoured base and rip-up clasts locally dispersed. The intense weathering of this sandstone made the sedimentary structures hard to identify. Some individual beds are cross-bedded or show current-ripple lamina (fig 12).

Facies A interpretation

Facies A is interpreted as the deposit of a delta-plain setting. This interpretation is based on similarities with various delta-plain deposits, such as the delta-plain of the Yallah Fan Delta, Southeast Jamaica (Wescott and Ethridge, 1980). The Yallah Fan Delta is a mixed wave- and river-dominated delta. Like facies A, the delta-plain of the Yallah Fan Delta is dominated by gray silty shale, with very fine- grained ripple

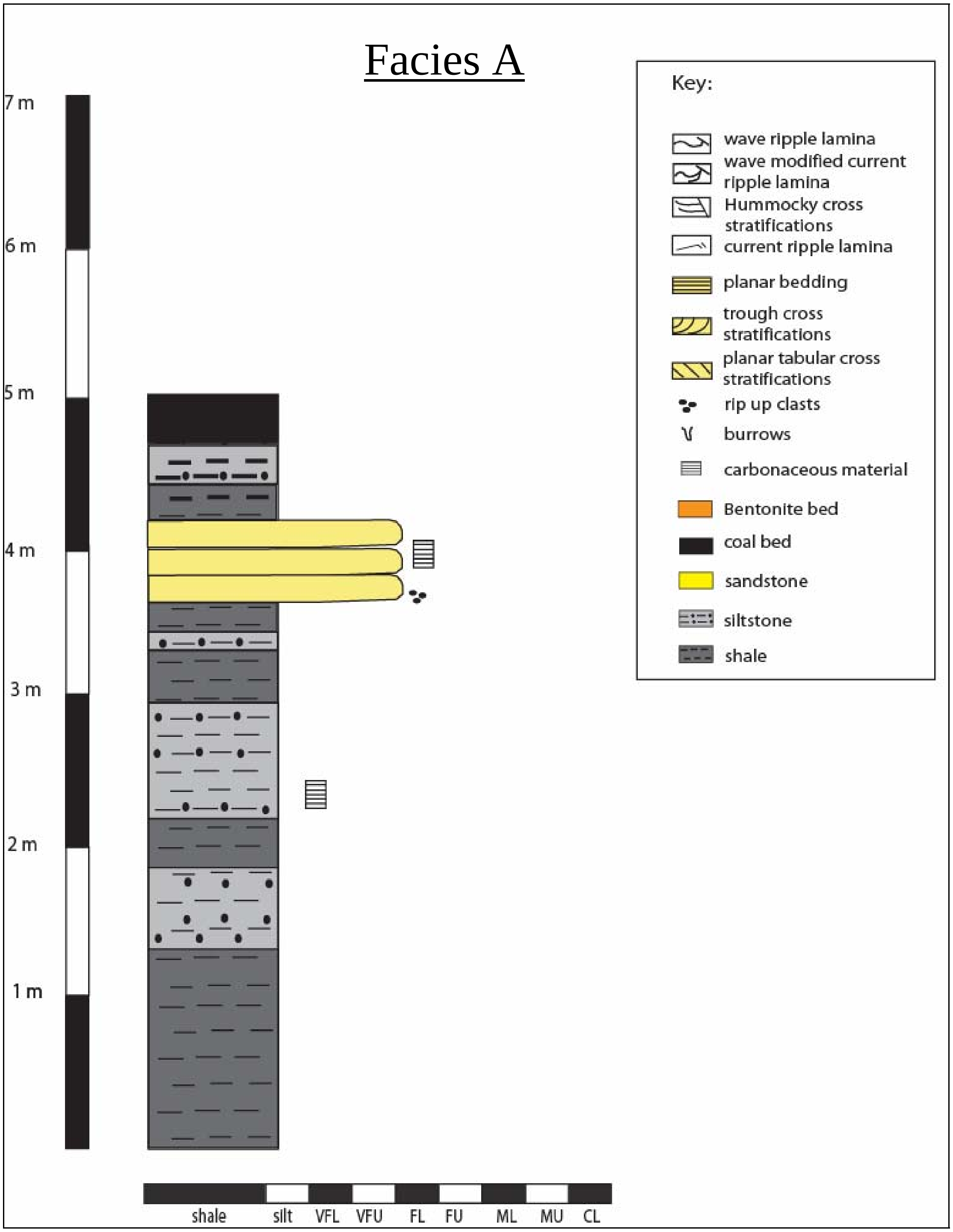

Fig 9: Schematic vertical representation of facies A showing fine-grained sediment with some thin sandstone beds.

Fig 10: Coal horizon at the top of facies A (showed by the arrows), overlain by silty shale from facies B. This coal is seen after trenching the unit (measured section locality Billy Creek). The rock hammer used as a scale is 15 cm long.

Fig 11: Facies A showing dark gray silty shale poorly exposed in measured section locality Billy Creek. This facies is located at the base of the Dakota Sandstone, just above the Burro Canyon Formation. The scale is 1.5 m high.

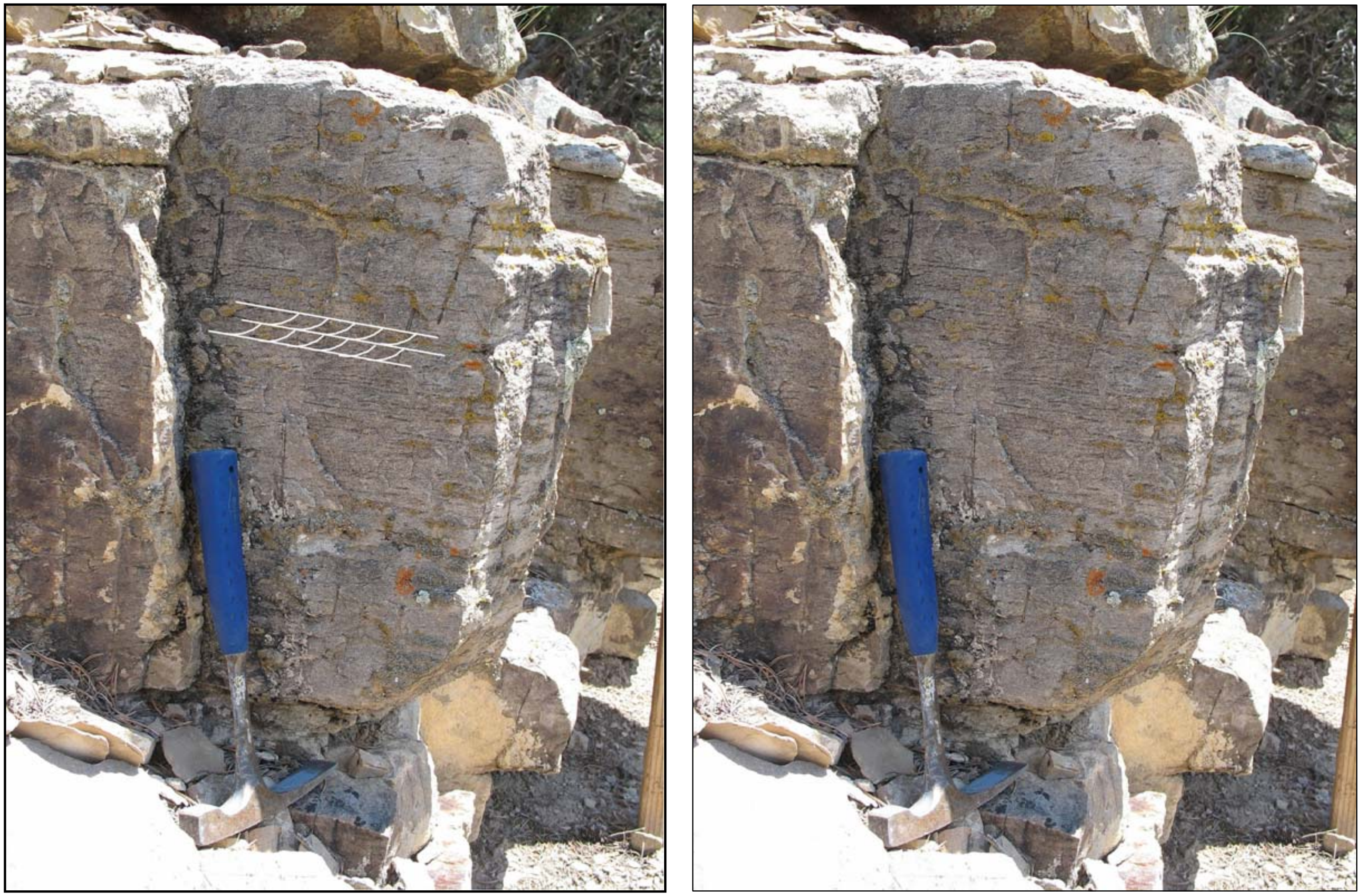

Fig 12: Sandstone interval within facies A showing current-ripple lamina (measured section locality Dutch Charlie 2). The current direction is from the right to the left. The rock hammer is 25 cm in length.

cross-laminated sandstones, and small-scale cut-and-fill structures interpreted as small channels. Delta-plain environments contain large volumes of overbank deposits. Reading (1996) divided the overbank deposits of the delta plain into distal (some distance from the channel), represented by the floodplain and proximal settings (close to the active channel), represented by levees and crevasse splay (fig 6). The silty shale of the Dakota Sandstone is interpreted as floodplain or distal overbank deposits. Floodplain sedimentation occurs during floods and is mostly from suspension (Reading, 1996). Wood and fine-grained plant material present in the floodplain are transported during overbank river stages and form carbonaceous material or coal horizons (Bernard et al., 1999). Such coal horizons and carbonaceous material are present in facies A. The thin sandstone beds described within facies A are suggested to represent small channel-fill sandstone or levee deposits. Levee deposits are ripple cross-laminated sandstone with small-scale cross bedding and plant fragments (Donaldson, 1974; Singh, 1972). Because of the poor exposures of facies A (i.e. the base is not always exposed), it is hard to distinguish whether these sandstone are levee deposits or small channel-fill deposits.

B. Facies B description

Facies B is an upward-coarsening succession ranging from laminated dark-gray silty shale interbedded with cm-scale sandstone beds at the base (fig 13) to predominantly sandstone beds approximately 20 cm thick (locally carbonaceous)

Fig 13: Upward-coarsening succession within the lower part of facies B showing alternating dark gray silt and brown sandstone (measured section locality Dallas Creek). The Jacob staff is 1.1 m in length.

at the top (fig 14, 15). It makes up half of the outcrops within the Dakota Sandstone in the Ridgway area and exhibits lateral continuity between the sections.

Facies B ranges from 1.5 to 7 m thick. The complete vertical succession of this facies begins at the base with a silty-shale interval of 1 m thick interbedded with thin (cm scale) wave-rippled sandstone beds. The siltstones are highly burrowed. Using the Droser-Bottjer (1986) classification, the ichnofabric index is identified as 5 (fig 16). Toward the middle of the succession, planar-bedded sandstone (~10 cm thick) (fig 17) to planar-bedded to rippled sandstone (fig 18) occurs with thin siltstone interbeds (5-8 cm thick). The rippled sandstone consists of current, wave or wave-modified current-ripple lamina (fig 19). Trace fossils are common and include *Planolites* (fig 20), *Arenicolites*, and *Skolithos*. Beds of planar bedding (20 cm thick) or planar bedded to wave-modified current-ripple laminated medium-upper sandstone (15 cm thick) dominate the top of the succession. Siltstone interbeds are very thin to absent (1 cm or less) in this upper part of the succession. Trace fossils are frequent throughout the facies and include *Arenicolites* (fig 21), *Skolithos* (fig 22), *Diplocraterion* (fig 23) and unidentified small sub-vertical and vertical burrows (fig 24, 25). These unidentified burrows are smooth walled, lined and passively filled. They are either vertical, curved or show a high angle to bedding. They average 2 to 3 cm long and 1 to 2 mm thick. One sample of these burrows showed a poorly developed J shape. These burrows may be *Arenicolites.*

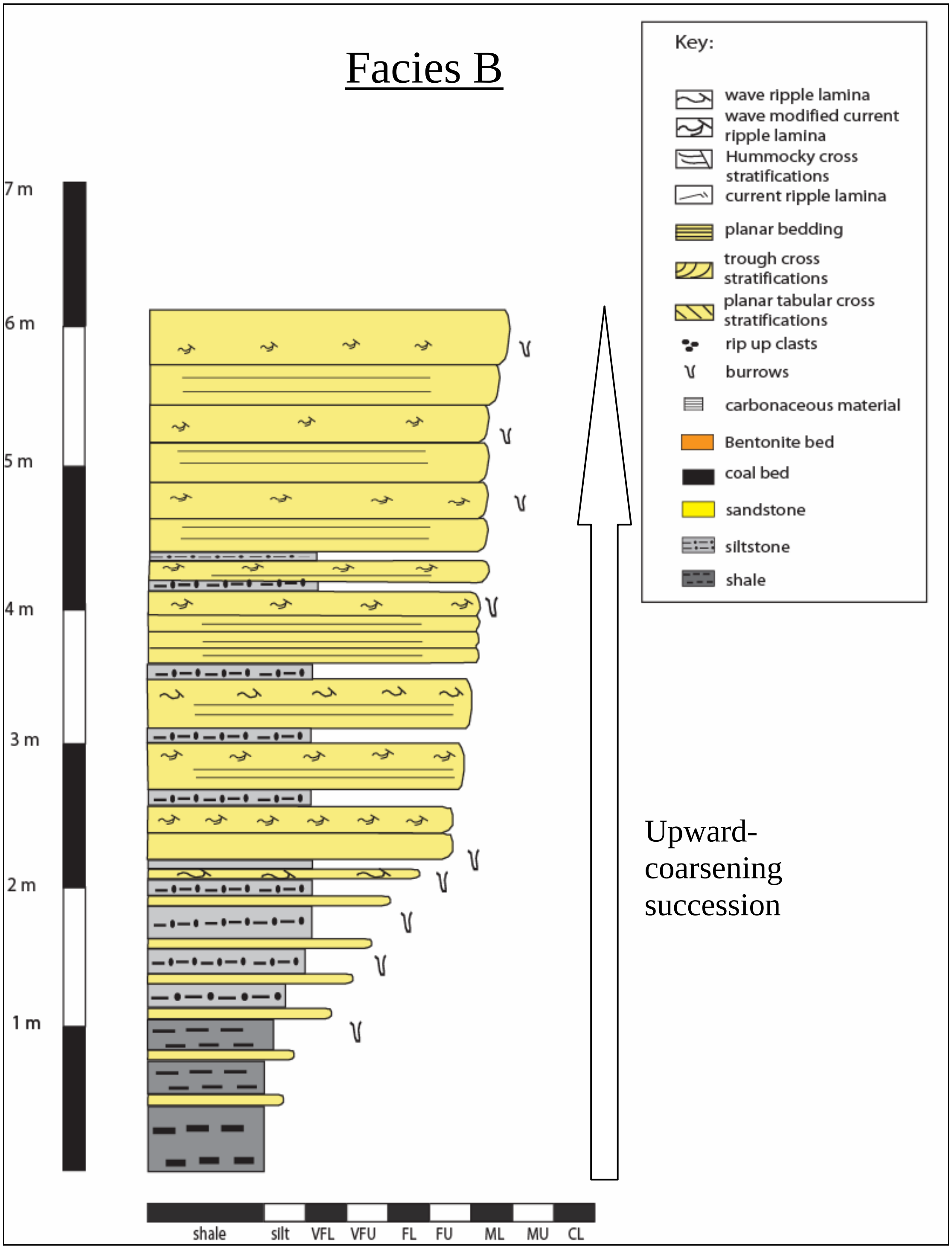

Fig 14: Schematic representation of facies B showing an upward-coarsening and upward-thickening bed succession within the Dakota Sandstone, Ridgway area.

Fig 15: Facies B showing upward-coarsening and upward-thickening succession of sandstone beds (measured section locality Billy Creek). The Jacob staff is 1.5 m.

Fig 16: Highly bioturbated siltstone within facies B. The beds have an ichnofacies fabric of 5 (measured section locality Billy Creek). The pencil is 1 cm in diameter.

Fig 17: Planar bedding within facies B (measured section locality Chaffee Creek 1). The pencil is 15 cm in length.

Fig 18: Planar bedding overlain by wave-modified current-ripple lamina (measured section locality Dutch Charlie 2). The pencil is 15 cm in length.

Fig 19: Wave-modified current-ripple lamina showing symmetric crest and unidirectional migration of the lee side in the ripple (measured section locality Dutch Charlie 2). The scale is 8 cm long.

Fig 20: *Planolites* showing horizontal burrows (measured section locality Chaffee Creek 2). The pencil is 15 cm in length.

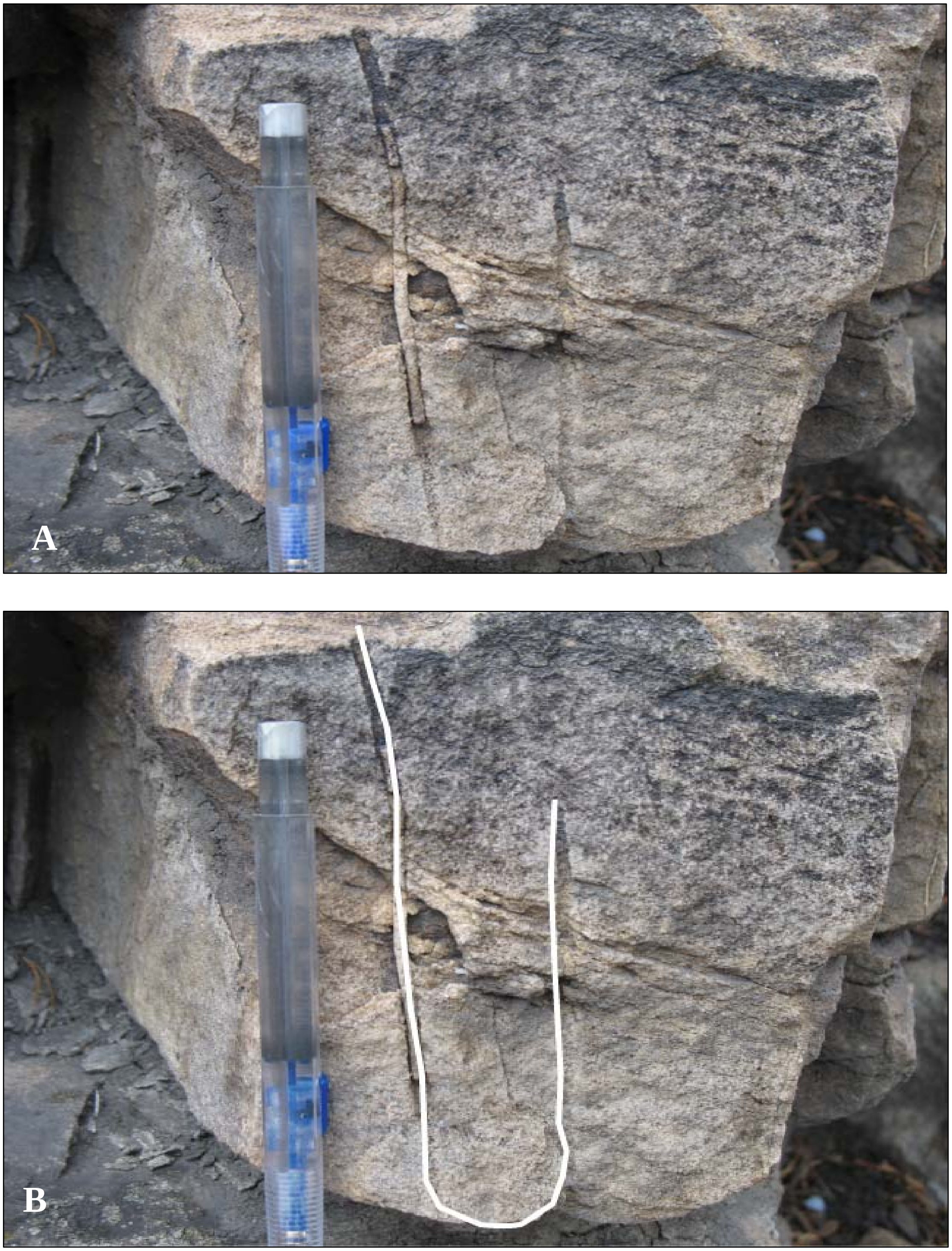

Fig 21: *Arenicolithes* within facies B showing U shape tube. The white line on picture B outlines the trace (measured section locality Chaffee Creek 1). The pencil is 1 cm in diameter.

Fig 22: *Skolithos* within facies B. This burrow is described as single, vertical tube of 2 mm thick (measured section locality Chaffee Creek 2). The pencil is 15 cm in length.

Fig 23: *Diplocraterion* showing U shape tube perpendicular to bedding. Internal spreite are very well preserved (measured section locality Dutch Charlie 2). The scale is in cm.

Fig 24, 25: Trace fossils described within facies B (measured sections localities Billy Creek, Dutch Charlie 3). The pencil is 1 cm in diameter.

Facies B interpretation

The upward-coarsening succession of facies B is interpreted as a delta-front deposit of a river-dominated delta with limited wave influence. The interaction between fluvial and marine processes is seen by the presence of current-, wave- and wave-modified current-ripple lamina (current-ripples modified by wave energy forming wave-modified current-ripple lamina, Hansen and MacEachern, 2005; Miall, 1984). Kamola and Van Wagoner (1995) described a similar succession within the Cretaceous Blackhawk Formation of Utah (the Sowbelly delta). The Sowbelly delta succession consists of distal delta front deposits at the base (showing intercalated cm-thick, burrowed, very fine-grained silty sandstone and fine-grained planar-bedded sandstone) and proximal delta-front at the top (consisting of planar-beds and planar-to current-ripple-laminated beds of sandstone). Facies B within the Dakota Sandstone shows the same succession with additional wave interaction. The interplay between river and wave processes also has been documented in the early to mid-Campanian basal Belly River Formation in the Ferrybank, Keystone, and eastern Pembina fields of central Alberta (Hansen and MacEachern, 2005). In this case, the upward-coarsening succession described for these deposits is identical to the one in facies B with the exception of additional wave influence in facies B.

The vertical trend in grain size and bed thickness within this facies is interpreted to reflect the progradation of a delta. At the base, silty shale material interpreted as distal delta-front changes progressively to sandstone beds that are interpreted as proximal delta front (Kamola and Van Wagoner, 1995). A gradational contact exists between distal and proximal delta-front. These two parts of the delta-front are not always present in the same outcrops. Limited wave influence is inferred from the presence of small wave-generated structures. The limited wave influence indicates that the sediments of this facies (delta-front) were deposited in a protected area, such as an embayment, where the wave energy was dissipated before it reached the coast.

C. Facies C description

Facies C consists of a sharp-based (fig 26), medium lower grained quartz arenite with rip-up clasts (cm in size) or carbonaceous lag (cm in size) overlying a scoured base (fig 27). It is about 3 m thick and does not show a consistent pattern in grain size through its thickness (fig 28). Facies C is lenticular and extends 10 to 100 m across the outcrops. Individual sandstone beds are 10 to 20 cm thick with planar tabular cross beds (fig 29), or trough cross beds (fig 30). Some individual beds contain current-ripple or wave modified current-ripple lamina (cm in size). *Arenicolites* is found commonly within this facies. This facies always truncates facies B.

In one location (Pa Co Chu Puk 3), facies C fines upward from sandstone at the base to interbedded sandstone and siltstone at the top (fig 31). In places, this facies is overlain by a coal bed of 10 to 50 cm thick. Internal scours can be present within facies C (fig 32).

Facies C interpretation

Facies C fills small channels. Because facies C is always associated with facies B (delta front), it represents a radial, bifurcating channel of a larger distributary channel. Distributary channels have been described as erosively based sands with basal lags, often truncating underlying deposits. Distributary channel-fills characteristically fine-upward (Coleman, 1981; Oomkens, 1970, 1974).

Fig 26: Scour base and rip-up clasts (cm) at the base of facies C (measured section locality Jacks’s Place). Rock hammer for scale is 25 cm long.

Fig 27: Carbonaceous lag at the base of facies C (measured section locality Pa Co Chu Puk 3). The scale is graded in cm.

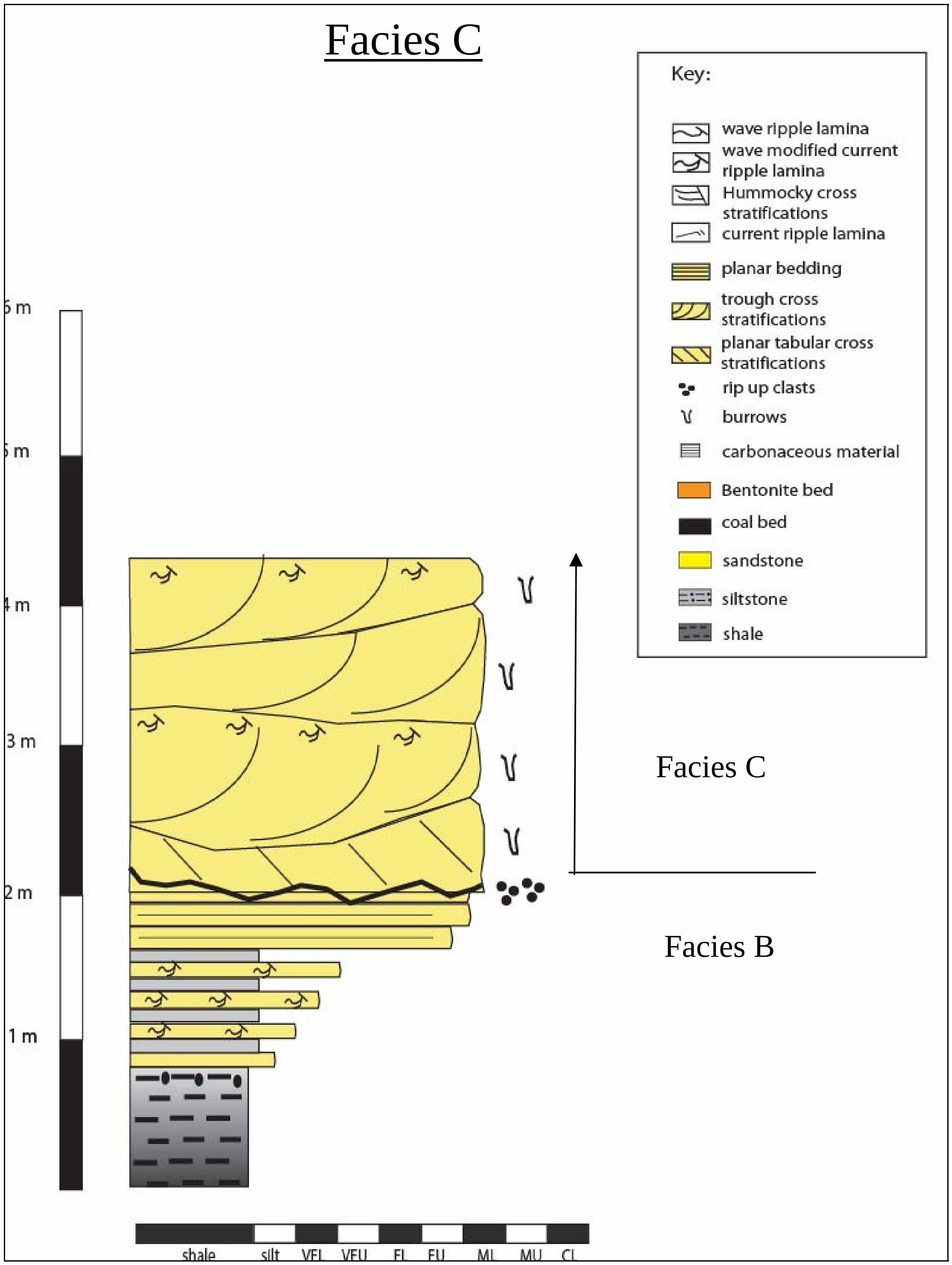

Fig 28: Schematic representation of facies C showing scour base with rip up clasts and trough cross stratification.

Fig 29: Planar tabular cross beds within facies C (measured section locality Billy Creek). The beds are about 15 cm thick. The scale is graded each 10 cm.

Fig 30: Trough cross beds within facies C (measured section locality Pa Co Chu Puk 2). Rock hammer is 25 cm in length.

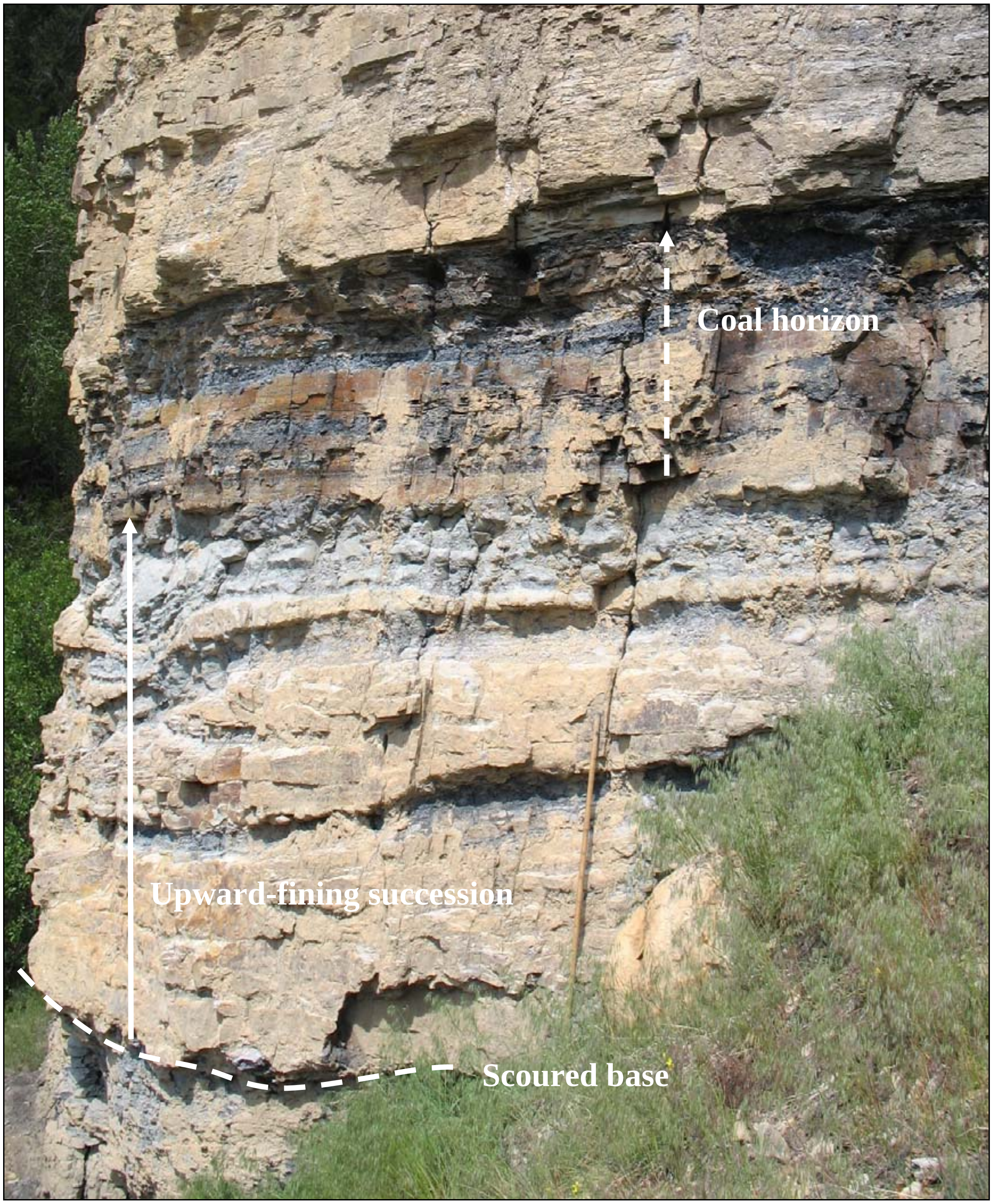

Fig 31: Upward-fining succession within facies C showing a coal horizon at the top of the succession (measured section locality Pa Co Chu Puk 3). The scale is 1.5 m long.

Fig 32: Internal scour described within facies C (delimited by arrows). The beds are about 15 cm thick and show planar tabular cross stratification (measured section locality Pa Co Chu Puk 2). The scale is 1.5 m.

Because of its small size (thickness) and its small lateral extent, facies C is interpreted as a radial bifurcating channel. Radial bifurcating channels carry sediment to small bay-fill crevasse-splay deposits (Coleman and Prior, 1981, definition). Bay-fill crevasse-splay deposits are formed between or adjacent to major distributaries (Coleman and Prior, 1981). The system of radial bifurcating channels allows bay-fill deposits to prograde seaward (Coleman and Prior, 1981). Bay-fill deposits range in thickness from 3 to 15 m (Coleman and Prior, 1981), comparable to facies B. Bay-fill deposits associated with numerous radial bifurcating channels of the Cubit Gap Crevasse of the Mississippi delta (Coleman and Prior, 1981) are similar to facies B and C of this study.

The interdistributary bays into which the bay-fill deposits prograde are usually open to the sea or connected to it by small tidal channels and contain brackish to marine water (Coleman and Prior, 1981). The presence of *Arenicolites* in facies C also suggests marine influence in these deposits.

D. Facies D description

This facies consists of light brown, fine-grained, well-sorted quartz arenite with hummocky-cross stratification (HCS) (fig 33). It is present in the upper half of the Dakota Sandstone and exhibits the greatest lateral continuity of any observed facies within the formation (along ~20 km). This facies has a sharp, erosional lower contact with the underlying facies.

Fig 33: Hummocky cross stratification (HCS), 3 m thick, within facies D (measured section locality Billy Creek).

Facies D ranges from 2.5 to 3 m thick (fig 34). The HCS is either amalgamated (fig 35) or consists of individual beds 0.1 to 0.3 m thick (fig 36), sometimes capped by wave-ripple lamina. *Arenicolites* and *Skolithos* are present locally.

Facies D interpretation

Facies D is interpreted as part of a wave-dominated, lower shoreface succession. The lower shoreface is defined by storm wave base at its seaward margin, and by effective fair-weather wave base at its landward margin (Komar, 1976). HCS occurs in fine sandstone to coarse siltstone (Dott and Bourgeois, 1982) and is proposed to form by strong surges of varied directions (oscillatory flow) that are generated by relatively large storm waves in the lower shoreface (Harms et al., 1975; Harms et al., 1982; Komar, 1976).

Individual HCS beds are described to have been formed in deeper conditions than amalgamated HCS (Van Wagoner et al., 1990). The presence of HCS is used to infer high wave energy. In this case, the sediments of facies D are interpreted to have been deposited in an open area where wave energy could affect the shoreface. Coastlines where wave and storm intensity are high and the effects of fluvial input are reduced usually straight coastlines (Reading, 1996).

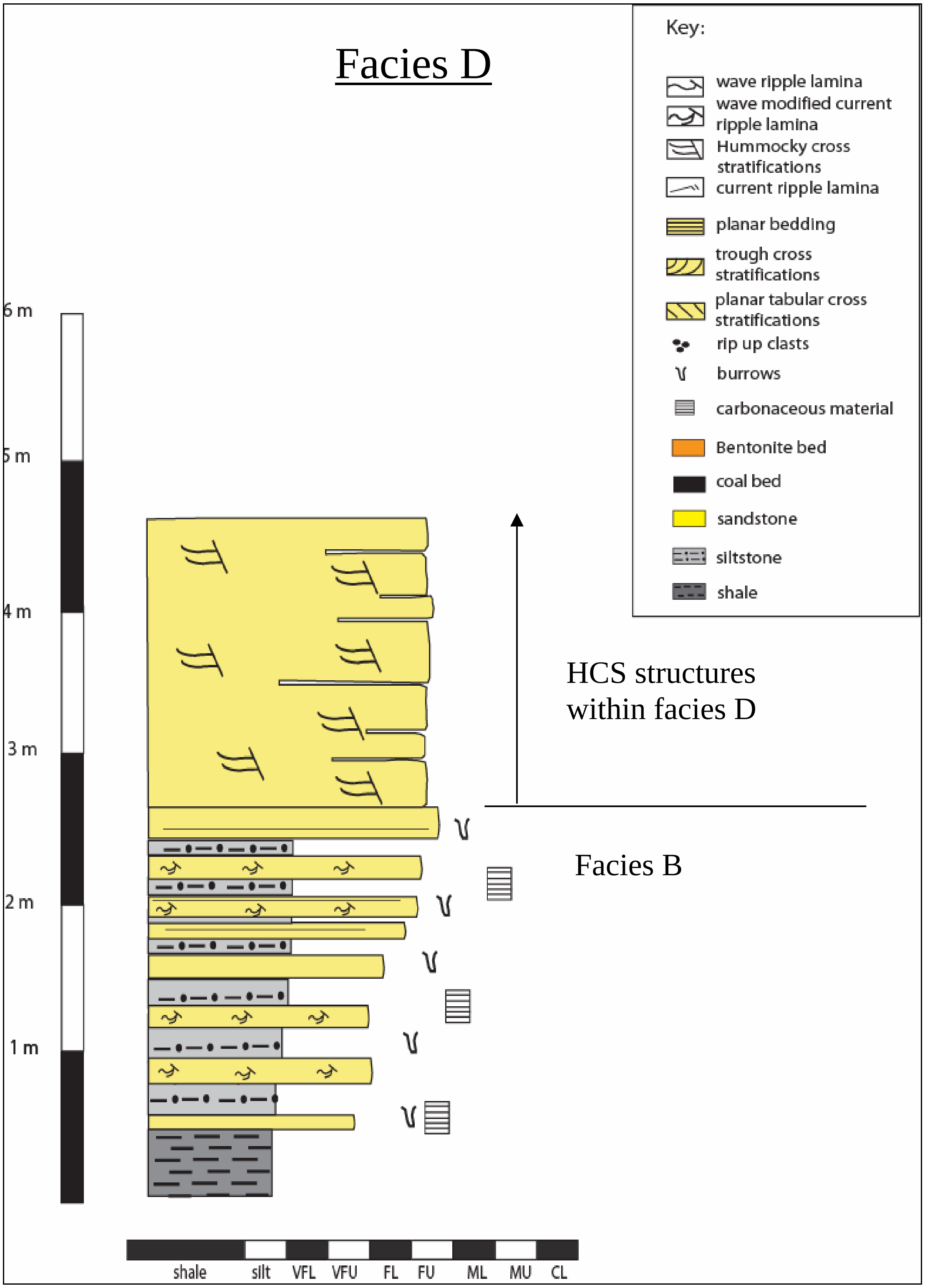

Fig 34: Schematic representation of facies D showing HCS structures.

Fig 35: Amalgamated HCS within facies D, exhibiting synformal swales and antiformal hummocks (measured section locality Billy Creek). Rock hammer is 25 cm in length.

Fig 36: Individual HCS cross stratified beds showing synformal swales and antiformal hummocks within facies D (measured section locality Billy Creek). Rock hummer is 25 cm long.

E. Facies E description

Facies E consists of a sharp-based, upward-fining succession ranging from medium-upper quartz arenite at the base to alternating silt and fine sandstone at the top (fig 36, 37). Cm-scale rip-up clasts are found at the base of the succession. Outcrop exposures do not allow for the exact width of this facies to be identified, but this facies shows greater lateral extent than facies C. Facies E is approximately 6 m thick. Bed thickness thins upward from 0.3 m to 5 cm and also thins laterally from 0.3 m to 0.1 m over a distance of a meter. The lower contact of this facies is erosional with a concentration of rip-up clasts (cm in size), which is overlain by compound cross-stratification in sets of 25 to 30 cm thick and current-ripple lamina. Load casts and soft-sediment deformation are present in places. Toward the middle part of the succession, cm-scale current-ripple lamina are more common and alternate with (10 cm) low-angle cross stratification. Toward the top of the succession, cm-scale wave-modified current-ripple lamina alternate with planar bedding and low angle cross stratification. At the top, siltstone beds thicken (from cm scale to ~ 10 cm thick), become more common and alternate with sandstone beds. A 20 cm coal bed is locally present at the top of the facies (fig 38). *Arenicolites* is sometimes present.

Lateral accretion is observed in facies E at some locations. It is visible from the distance but difficult to trace in the outcrop. Laterally, within a single bed, grain-size changes from sand to silt. Facies E is a cliff/ledge former. It is only present in small number of measured sections (fig 41).

Fig 36: Sharp-based upward-fining succession of facies E (measured section locality Dutch Charlie 2). The exposed part of the Jacob staff is 1.3 m in length.

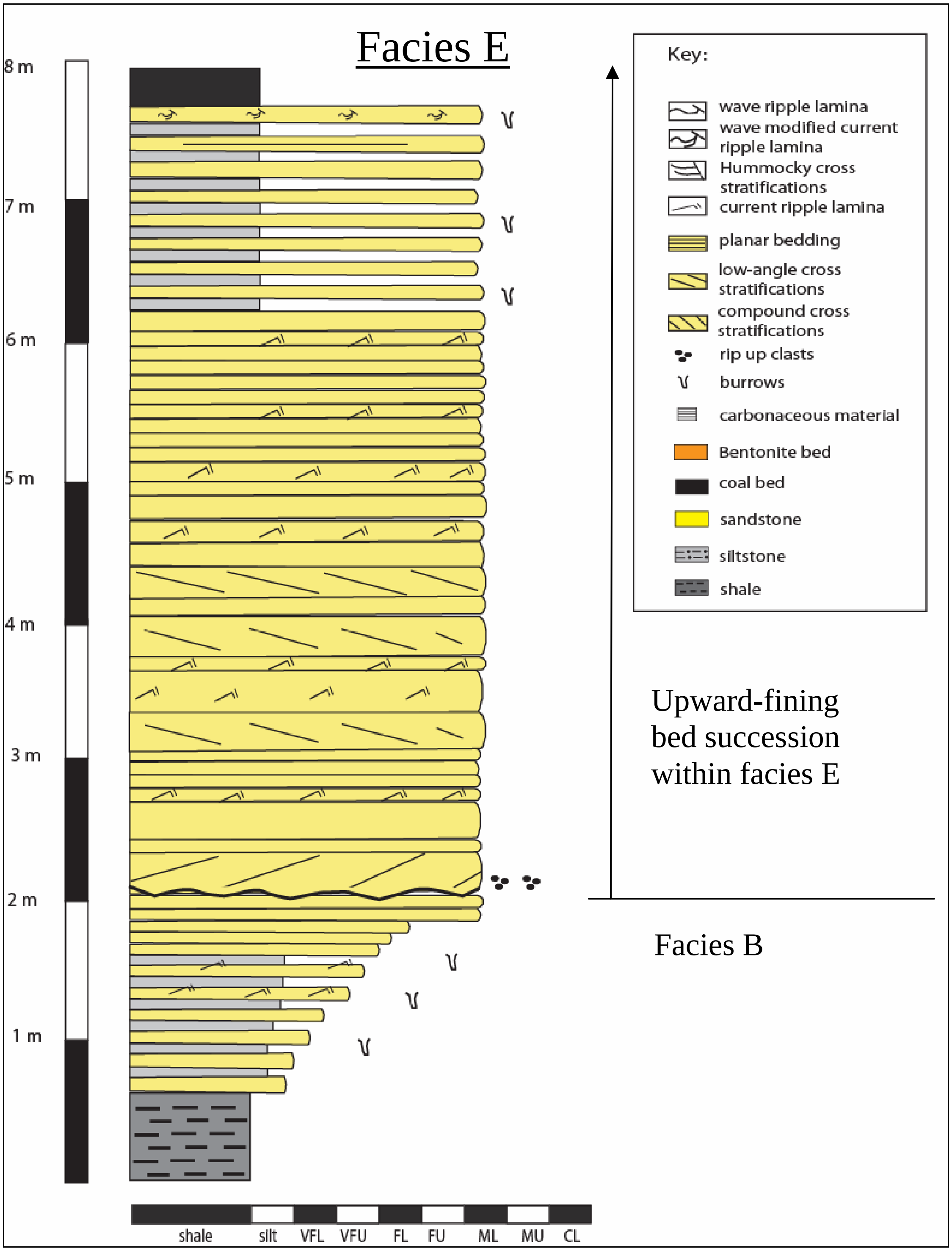

Fig 37: Schematic representation of facies E showing a scour base with rip-up clasts and an upward-fining succession.

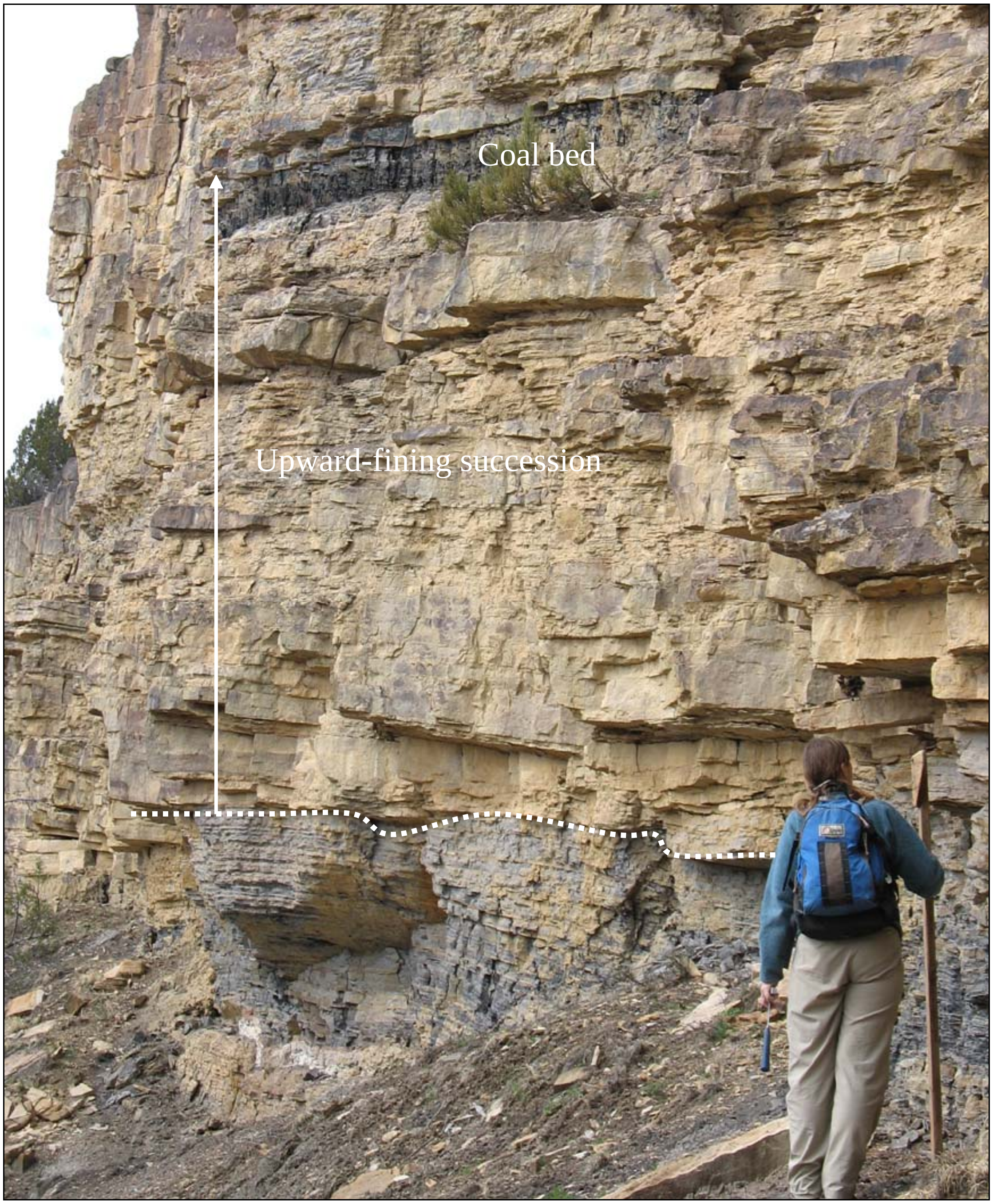

Fig 38: Scoured base and upward-fining succession of facies E, with coal bed at the top (measured section locality Dallas Creek). The scale is 1.5 m.

Facies E has some similarities with facies C (scour base, rip up clasts and grain size) but differs in thickness, vertical succession and the presence of the lateral accretion.

Facies E interpretation

Facies E is interpreted as to be the fill of a sinuous fluvial channel. A similar vertical succession of sedimentary structures and the alternation of sandstone and siltstone are present in the Sudmoor Point Sandstone and are interpreted as the deposit of meandering channels (Stewart, 1981).

The lateral change in bed thickness associated with compound cross-stratification are interpreted to represent deposition from compound bars within a channel (Bridge, 2003). The vertical decrease in grain-size and bed thickness, as well as a change in the sedimentary structures from compound-cross stratification at the base to low angle cross-stratification, planar bedding and wave ripples at the top of the succession reflects progressively weaker flows as the channel fills (Bridge et al., 1986b; Williams and Rust, 1969). The change from compound-cross stratification at the base to planar bedding at the top indicates also progressively shallower water depth (Bridge, 2003). Ripples at the top of the planar bedding indicate falling flow stage, and a decrease in the current energy as the channel fills (Allen, 1964; Leeder, 1973). Some marine influence is seen by the presence of *Arenicolites* and wave modified current ripple lamina present at the top of the facies.

F. Facies F description

Facies F is a well-bedded medium-grained quartz arenite, with a scoured base (fig 39). Rip-up clasts are present locally. Grain size is constant vertically and laterally throughout the facies. This facies is approximately 7 m thick and is present at the top of the Dakota Sandstone. It is seen in only three sections (Dutch Charlie 2 and 3, and Dallas Creek). Facies F is the thickest facies recognized within the formation. Like facies E, this facies is laterally continuous and acts as a cliff or ledge former.

Facies F shows an upward-thinning of sandstone beds. The thickness of individual sandstone beds changes from ~0.9 m at the base to ~15 cm at the top. The basal scour is overlain with cm-scale rip-up clasts, and planar tabular cross beds (high-angle cross-stratification; fig 40). Individual planar tabular cross-beds form bedsets within this facies. Grain size is constant from the base to the top of each bedset. The vertical succession is capped by ~10 cm of wave-modified current ripple lamina. Facies F and C show similarities (scoured base, rip-up clasts, absence of upward-fining trend in grain size, similar grain size, tabular cross stratifications). The difference between these two facies is in total thickness, lateral extent, individual bed thickness, and sedimentary structures.

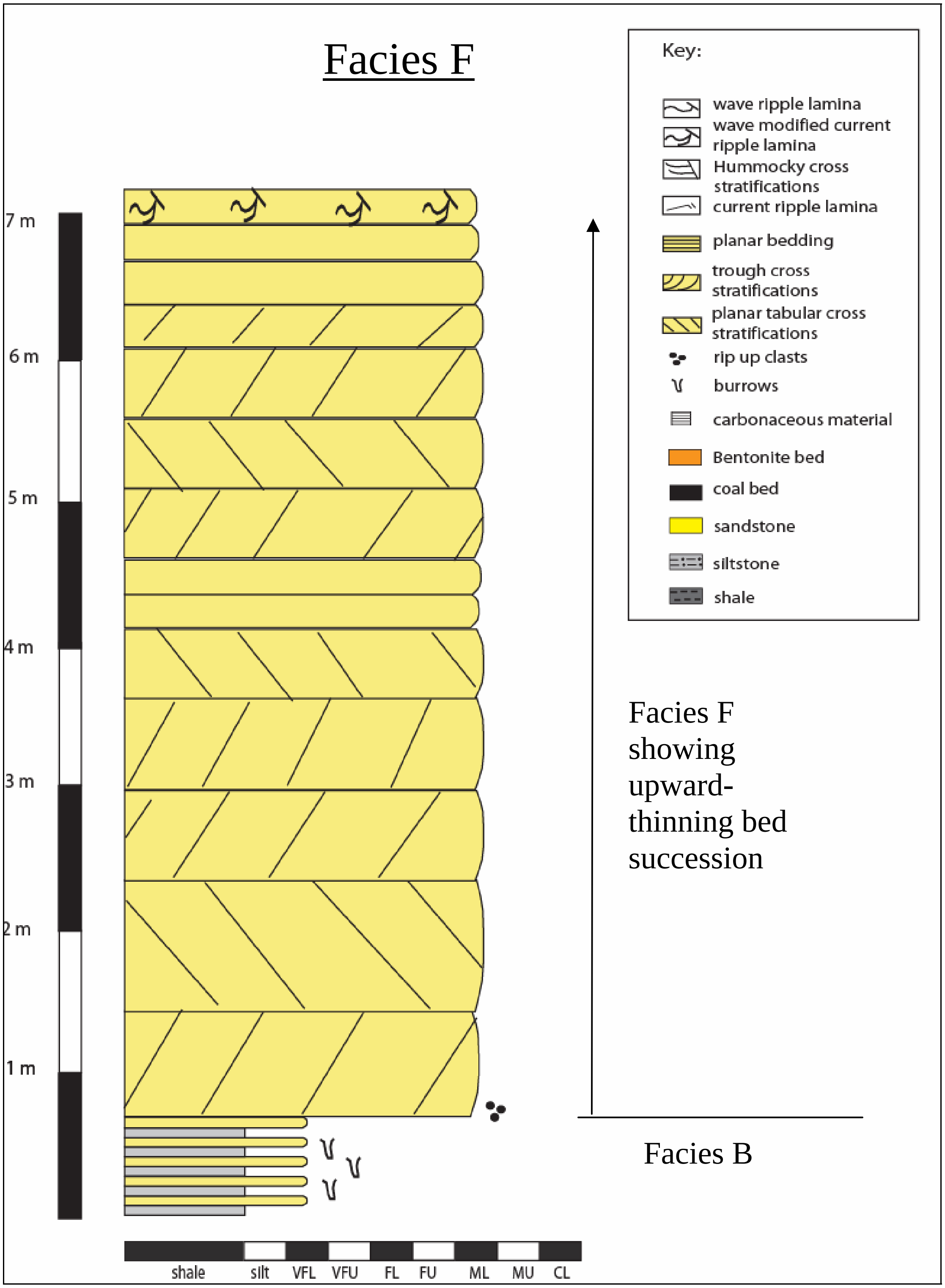

Fig 39: Schematic representation of facies F showing an upward-thinning bed succession.

Fig 40: Planar tabular cross stratification within facies F (measured section locality Dutch Charlie 2). The Jacob staff is 1.5 m in length.

Facies F interpretation

This facies represents a channel-fill sandstone. Bed thickness, the absence of an upward-fining trend and sedimentary structures (planar tabular cross beds) within facies F are interpreted to indicate high-energy environment.

The migration of 2-D bedforms (~1 m high) resulted in the formation of planar-tabular cross-stratification. These planar-tabular cross-stratification bedsets are interpreted as parts of amalgamated bars (Allen, 1970; Bridge, 2003; Fisher and McGowen, 1969; Jackson, 1976; Smith, 1970). A bar is defined as a bed form with length proportional to channel width and height proportional to channel depth (Reading, 1996). In this case, the thick bars within this facies are related to the width and depth of the channel within facies F. Usually, individual bars show an upward-fining trend in grain size (Reading, 1996), however, the bars within facies F do not show an upward-fining trend. This may be explained by the fact that the upper part of each bar has been eroded by the overlying bar. Wave-modified current-ripple lamina, present at the top of the channel-fill, indicate decrease in flow energy. They also indicate the interaction between fluvial and wave processes.

II. Correlation

Nine of the eleven measured sections have been correlated using a sequence stratigraphic approach. The datum used in this correlation is the Dakota Sandstone-Mancos Shale contact. This boundary represents a major deepening event followed by the deposition of the Mancos Shale. The correlation line is oriented north-south covering a distance of 22 km. Although the paleoshoreline trend of the Dakota Sandstone is hard to establish throughout the study area, the nine correlated sections are interpreted to be oriented oblique to the paleoshoreline trend, because a significant change in facies or water depth is not seen laterally within the same parasequence. Parasequence boundaries (PSB), and sequence boundaries have been traced laterally along the nine sections. PSB are roughly parallel to each other between the nine measured sections indicating no significant change in facies thickness or accommodation during the deposition of the Dakota Sandstone. Some facies within the Dakota Sandstone are present along almost all the sections, such as facies D (lower shoreface). Others are discontinuous and are present in few sections, such as facies F (fluvial channel). In the lower half of the Dakota Sandstone, deltaic deposits have limited wave influence. In the upper half of the formation, wave influence increases, as seen in the HCS beds within the lower shoreface setting. This change has been explained by the fact that the shoreline configuration changed from an embayed setting (lower part of the formation) to straight shoreline (upper part of the formation), and to another embayed setting at the top of the formation.

Chapter III: Sequence-stratigraphic interpretation

A sequence-stratigraphic approach has been applied to the Dakota Sandstone within the Ridgway area to place the strata of this formation in a genetic framework and to investigate lateral continuity-discontinuity of the six facies described in chapter II. Following the approach and definitions of Van Wagoner and others (1990), genetically related facies have been grouped into parasequences. Each parasequence is bounded by a parasequence boundary represented by a flooding event (rise in sea-base level). Parasequences have been also grouped into sequences. Each sequence is separated by a sequence boundary represented by a fall in sea-base level. Correlation of the nine stratigraphic sections reveals the identification, distribution and the lateral extent of parasequences and sequences (fig 41). A sequence-stratigraphic interpretation of the nine sections within the Dakota Sandstone reveals the presence of three sequences (with two incised-valley fills), eleven parasequences and four parasequence sets (fig 41, 42).

I. Parasequences

Eleven parasequences (PS) have been identified in the Ridgway area (fig 43). Parasequences are described as genetically related units bounded by flooding surfaces or their correlative conformities (Van Wagoner, 1990).

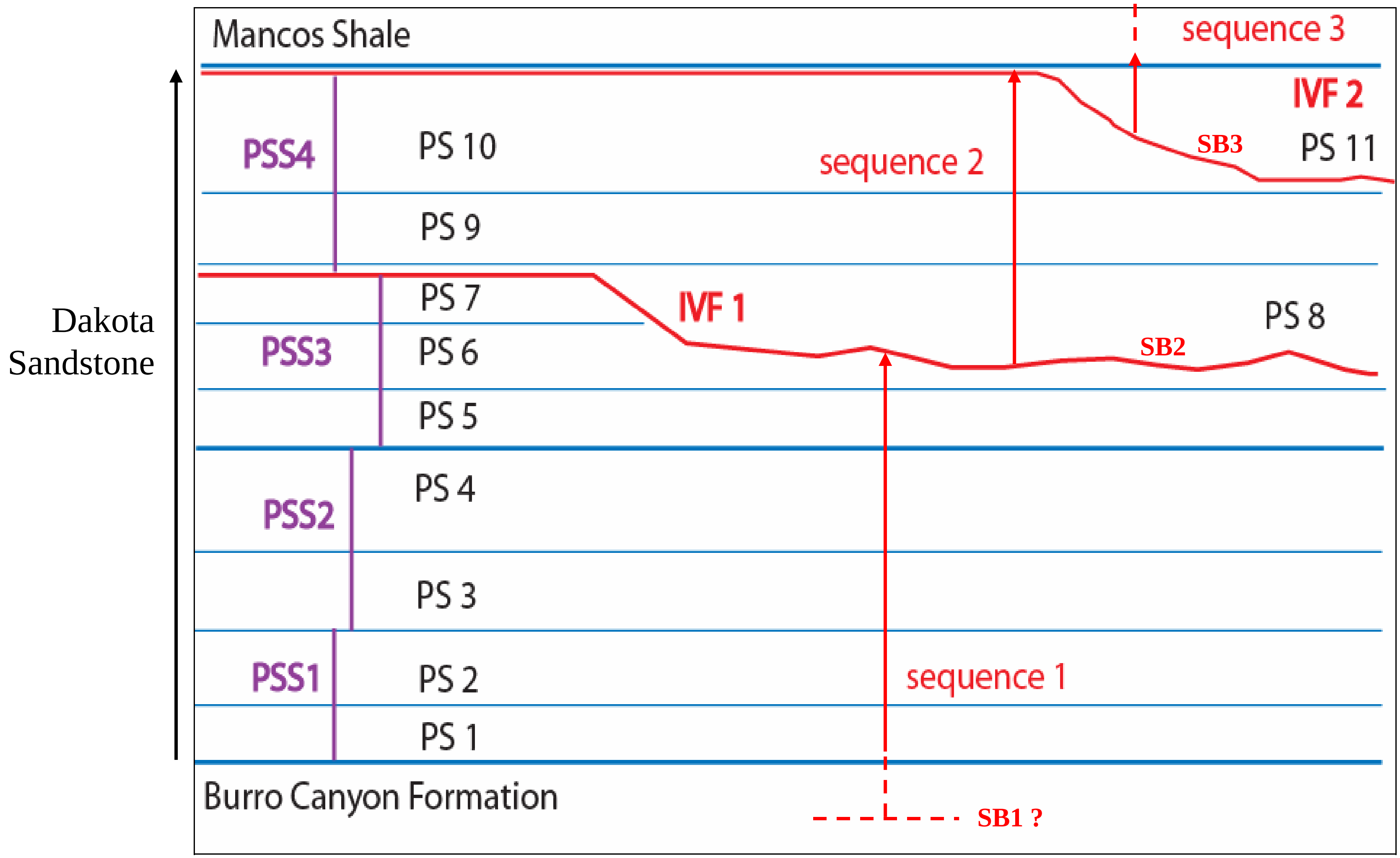

Fig 42: Schematic illustration of sequence stratigraphic interpretation of the Dakota Sandstone in the Ridgway area.

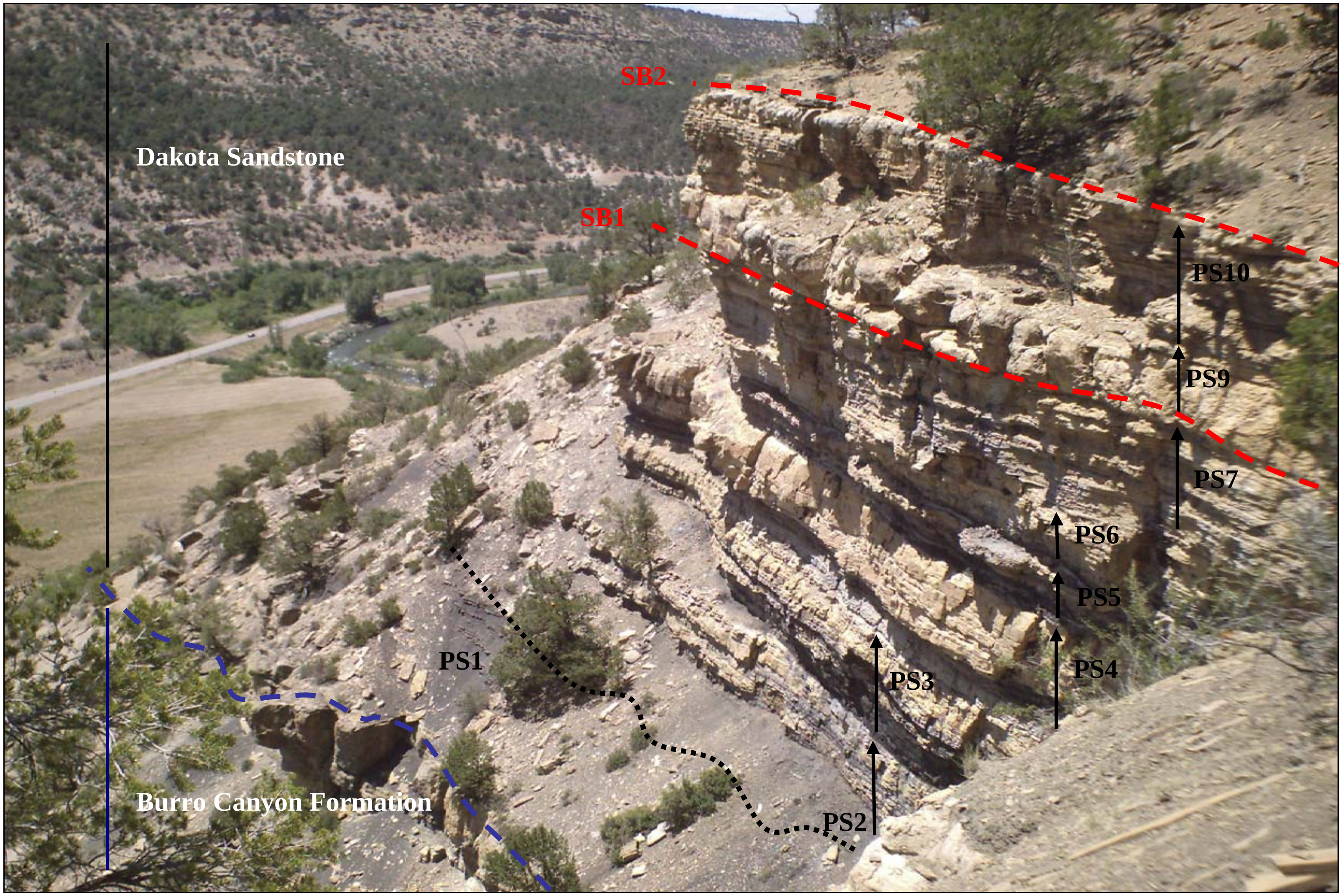

Fig 43: Photomosaic of Chaffee Creek 1 section showing 9 parasequences. Parasequence 8 and 11 are not seen in this location.

Parasequence boundaries are always identified by a deepening event which juxtaposes deeper-water facies on shallower-water facies (fig 44). The parasequences within the Dakota Sandstone are small in size with thicknesses varying from 1 to 7 m (fig 45).

Parasequences contain delta plain, delta front, radial bifurcating fluvial channel (distributary channel), fluvial channel (sinuous or high-energy) and lower shoreface deposits. Parasequences are composed of either one or multiple genetically related facies. For example, parasequence 9 contains only one facies, a lower shoreface succession (facies D). Parasequence 3 contains multiple facies, including radial bifurcating fluvial channel (facies C), which is traced laterally to delta front (facies B). In the lower half of the formation, parasequences are laterally continuous across the study area. In the upper half of the formation, parasequences are laterally truncated by a sequence boundary or occur within incised valleys and onlap sequence boundaries (which coincide with the walls of the incised valleys).

Within the same parasequence, deltaic subenvironments change facies laterally for over a distance of 3 to 4 km. These lateral changes help establish the size of individual deltas. Deltas are estimated to be small in size, approximately 3 to 4 km in width.

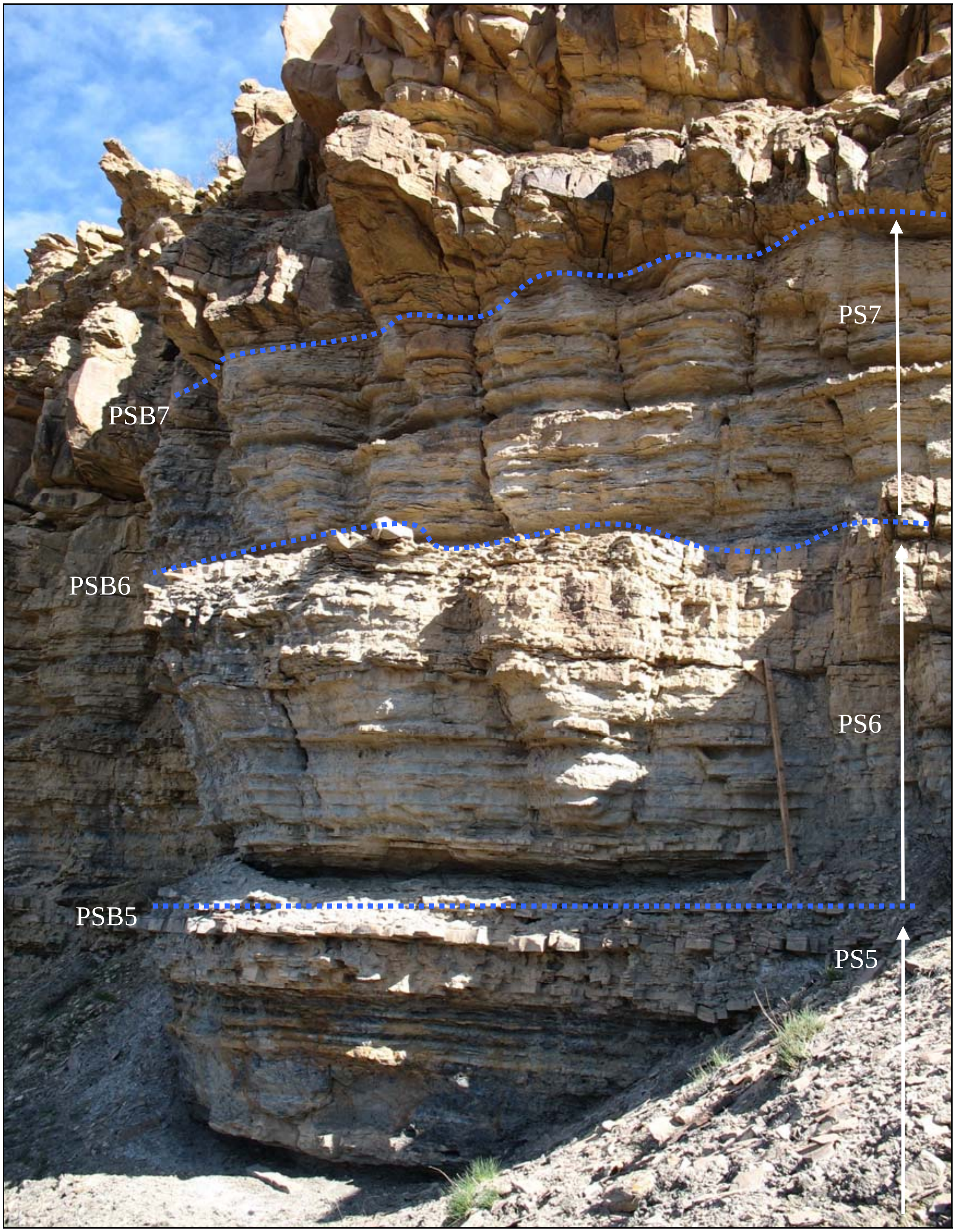

Fig 44: Three parasequences showing upward-coarsening successions of deltaic facies (facies B). The Jacob stuff is 1.5 m long. Each parasequence is approximately 2 m thick. The blue lines (PSB) represent flooding surfaces (deepening events) (measured section locality Billy Creek).

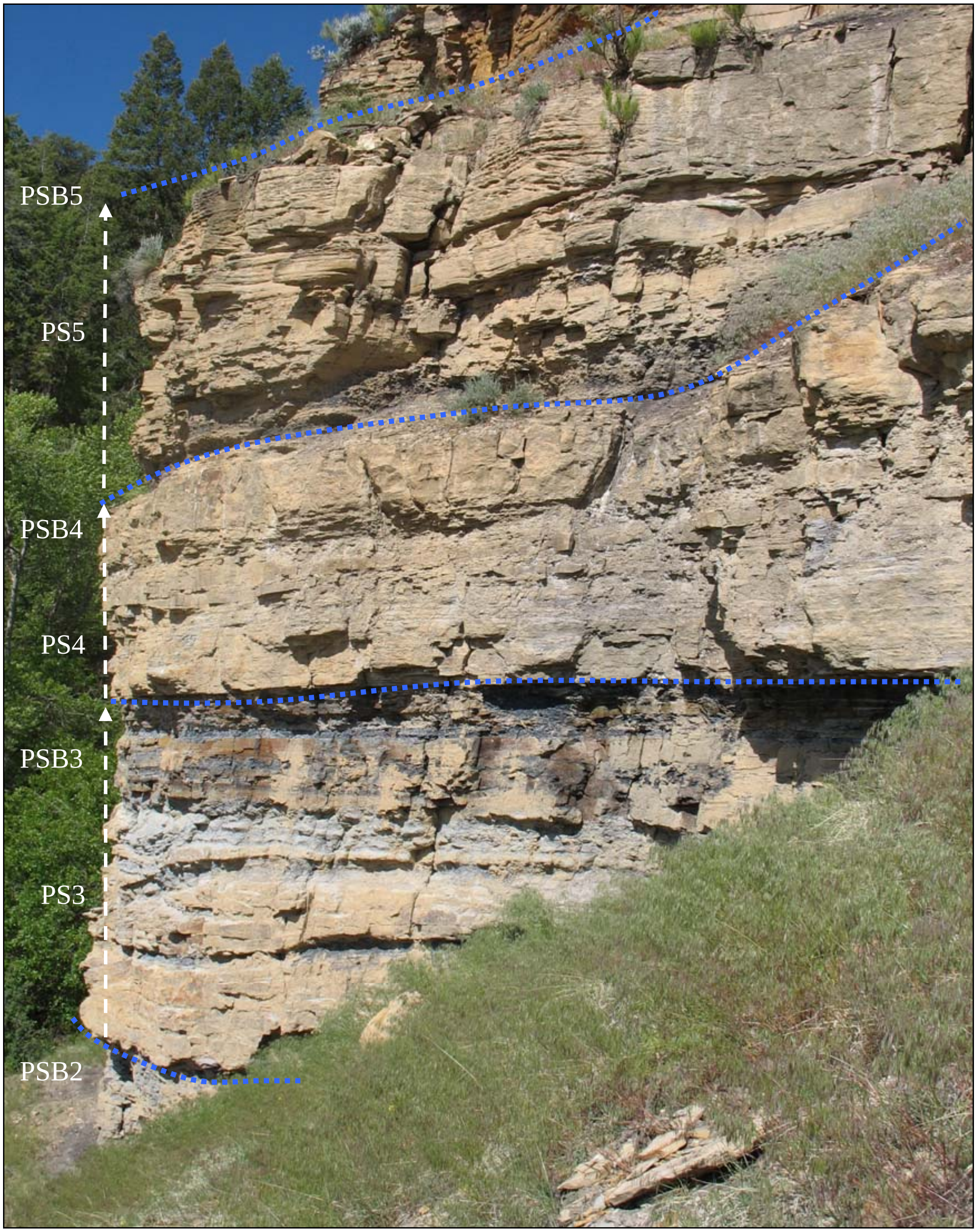

Fig 45: Three parasequences within Pa Co Chu Puk 3 section. Each parasequence is bounded by a parasequence boundary represented by a blue line. The basal PS (4 m thick) contains channel-fill SS (facies C). The middle PS (2.5 m thick) contains delta front facies (facies B). The upper PS (3 m thick) contains delta front and radial bifurcating distributary channel facies.

II. Sequences

The Dakota Sandstone comprises 3 sequences. From the base to the top of the formation, these sequences are designated as S1, S2 and S3 (fig 46, 47). Sequences are defined as a conformable succession of units bounded by sequence boundaries (fall in sea-base level) (Van Wagoner, 1990). The basal part of sequence 1 is within the Burro Canyon Formation and is not included in this study. Sequence boundary SB2 separates sequence 1 from sequence 2. Sequences 2 and 3 are bounded by SB 3. These sequence boundaries are recorded either as large-scale erosional surfaces or their laterally equivalent interfluve expressions. Only the stratigraphically lower part of S3 occurs at the top of the Dakota Sandstone, the upper portion of it is within the Mancos Shale. The sequence boundary (SB4) which occurs at the top of sequence 3 is within the overlying Mancos Shale.

Sequence 1 starts in the Burro Canyon Formation and continues within the Dakota Sandstone. It is the thickest sequence within this formation (about 20 m). It includes 7 parasequences (from PS1 to PS7). A single well-defined parasequence stacking pattern is not evident from PS1 to PS7 (fig 48). PS 1-2 are retrogradationaly stacked forming parasequence set 1 (PSS1). PS 3 to 4 make up parasequence set 2 (PSS2) and show an aggradational trend. PS 5 to 7 form parasequence set 3 (PSS3) and are also aggradationally stacked. Parasequences within PSS2 are composed of delta front and distributary channel facies. Parasequences within PSS3 are represented by distal and proximal delta front. For this reason, PPS2 and PSS3 have been differentiated.

Dutch Charlie 2 measured section

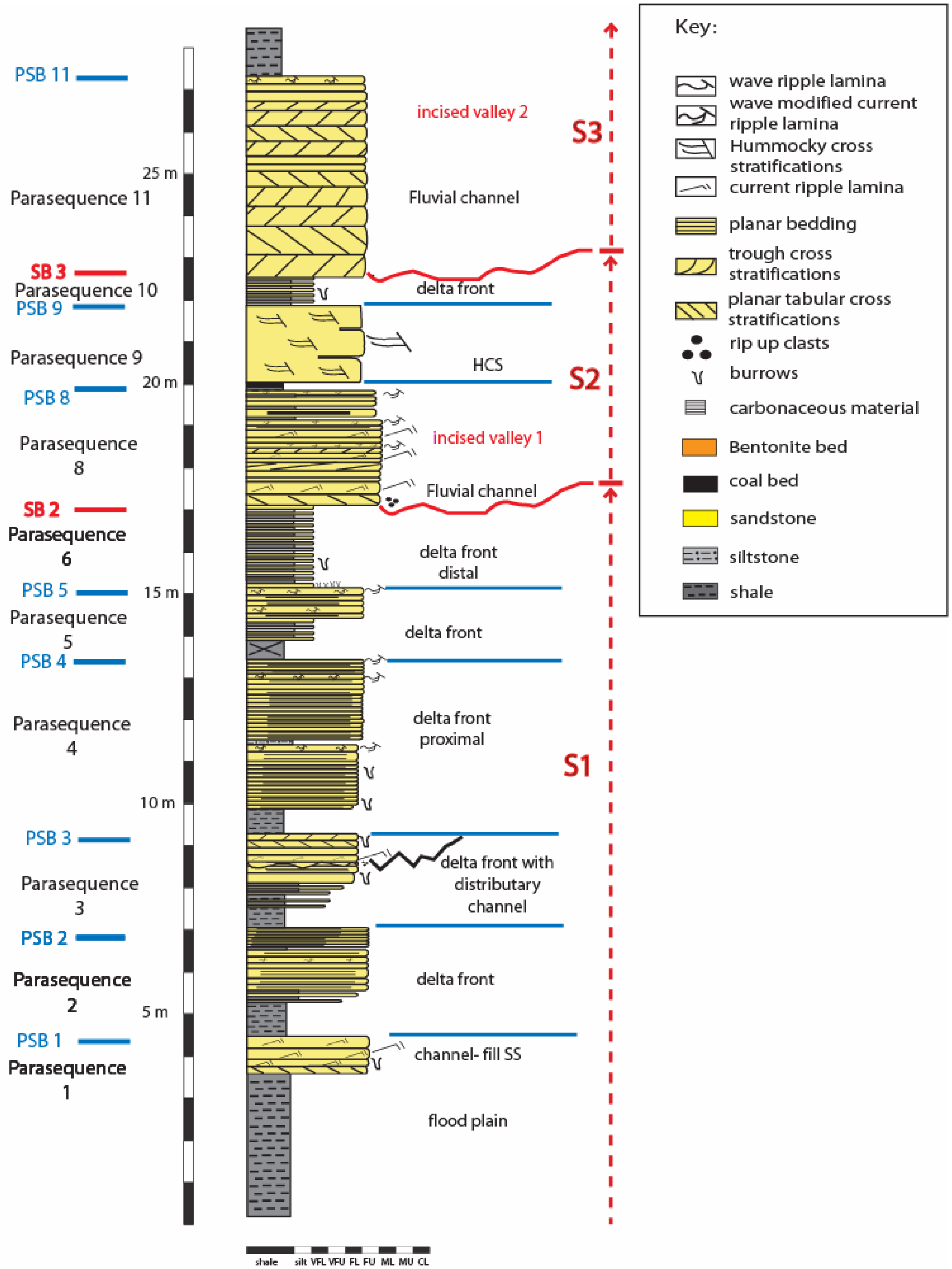

Fig 46: Schematic representation of Dutch Charlie 2 measured section showing three sequences (S1, S2 and S3).

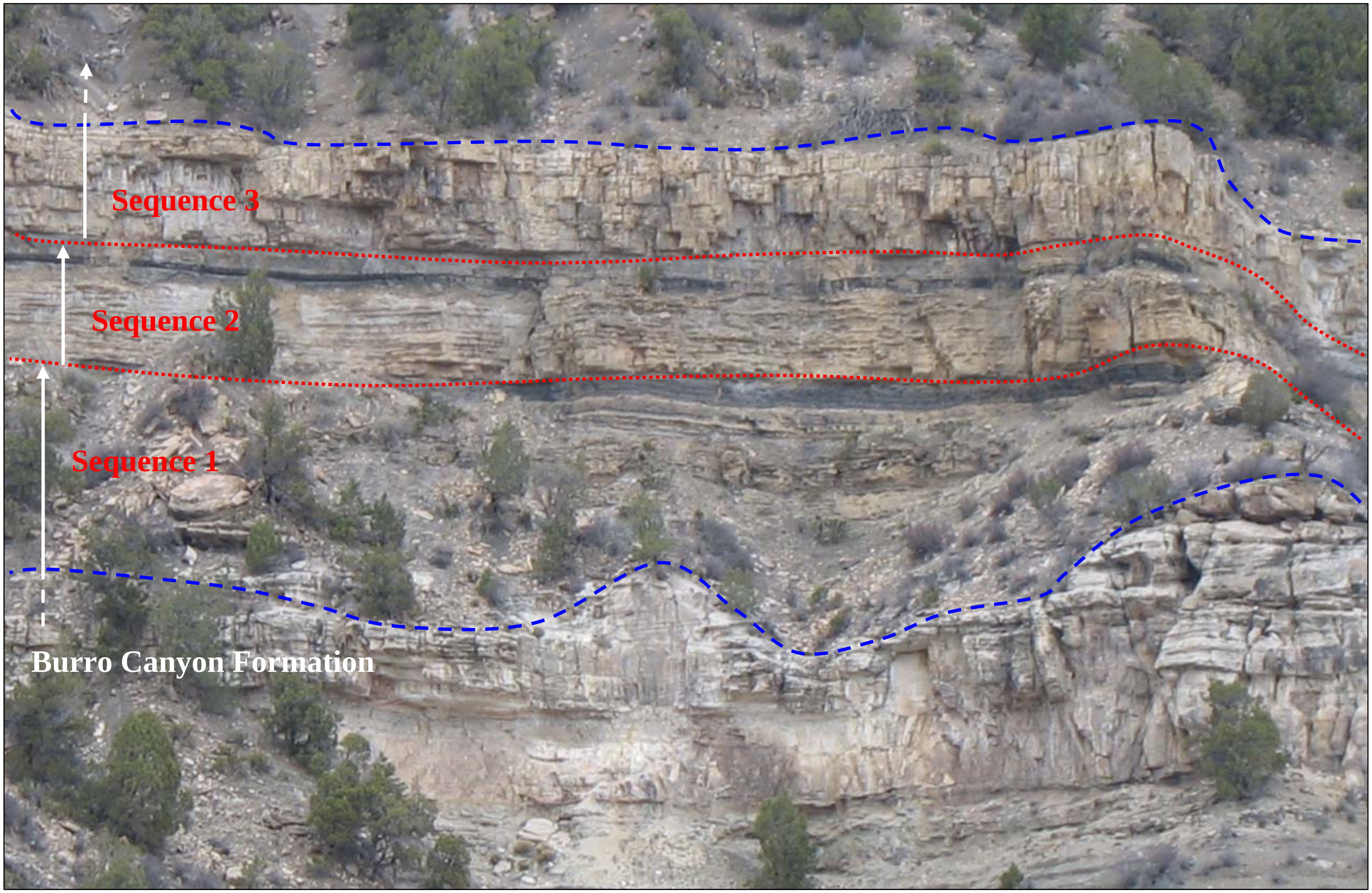

Fig 47: Panoramic picture of the Dallas Creek measured section locality showing 3 sequences within the Dakota Sandstone. The sequences are labeled from the base to the top S1, S2 and S3. The blue lines represent flooding events (PSB).

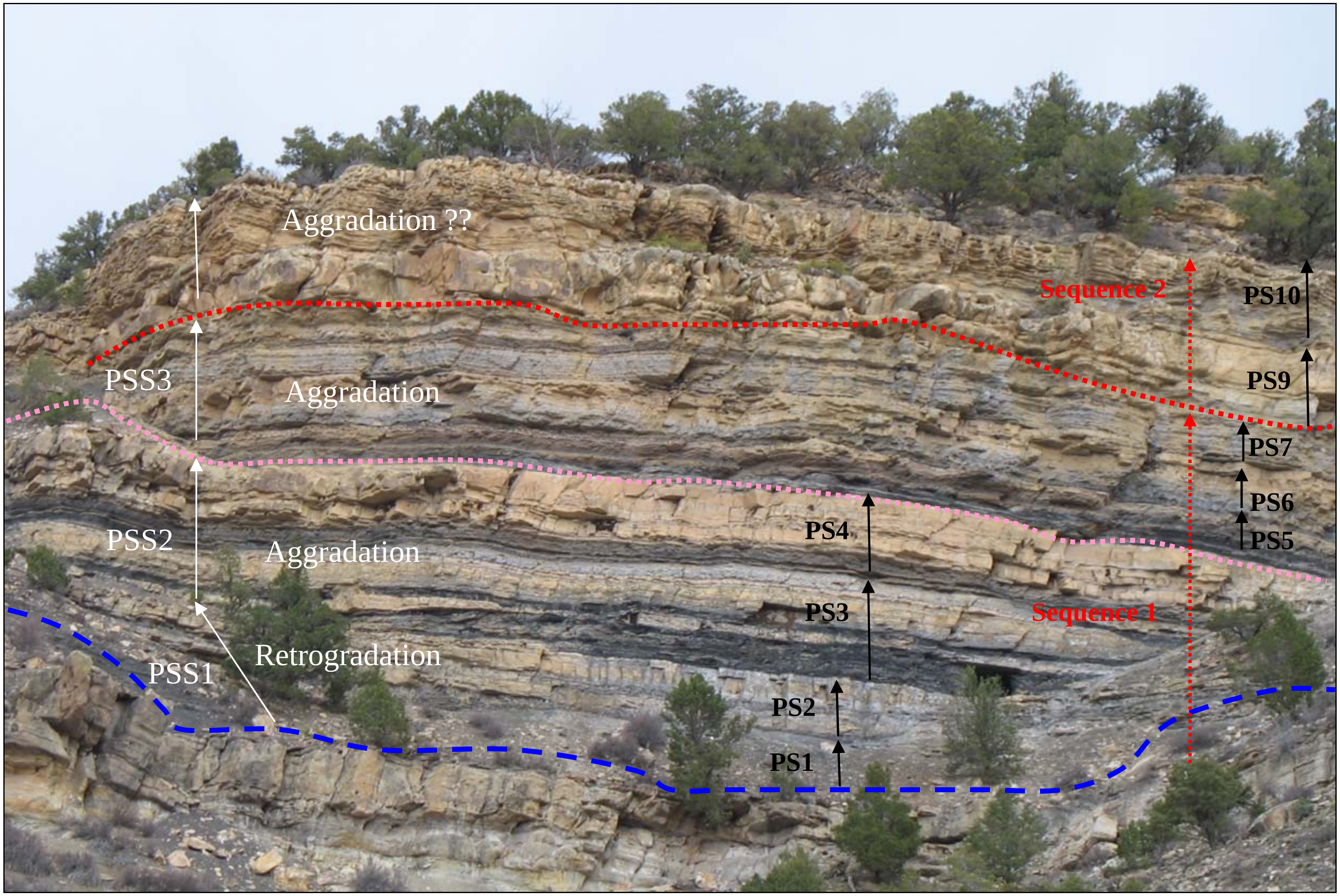

Fig 48: Panoramic picture of Chaffee Creek 1 measured section locality showing the 3 parasequence sets and their stacking pattern within the first sequence (S1). Parasequences 8 and 11 are not present in this location.

The multiple stacking patterns for PS 1 to 7 may be due to the internal facies complexity inherited in a deltaic setting (rapid lateral facies change). PS7 and the upper part of PS6 are truncated laterally by the base level/sea level fall which formed SB2.

The total thickness of sequence 2 is 10 m. Sequence 2 includes three parasequences (PS 8-10). These parasequences include fluvial channel (facies E), lower shoreface (facies D) and delta front (facies B) deposits. The basal sequence boundary (SB2) shows erosional relief of 4 m. SB2 is locally defined by a thick horizon (up to 70 cm thick) of rip-up clasts, seen in the Pa Co Chu Puk 3 measured section locality (fig 49, 50). The interfluve expression of SB2 is a non-descriptive surface, recognized only through the correlation of the nine measured sections.

Erosional relief created by SB2 formed an incised valley (IV1). This incised valley is filled with fluvial deposit (facies E) of PS8. The fluvial deposits onlap the truncational surface of the IV1. The remaining parasequences 9 and 10 are either within the transgressive system tract or the highstand system tract. A flooding event (PSB) separates the IVF1 (PS8) from the overlying two parasequences (PS9 and PS10) at the top of the sequence. PS 9 represented by lower shoreface facies (facies D), and is the first parasequence to be deposited after the incised valley has filled. PS9 is interpreted to indicate a change to a more open water shoreline setting where waves freely affected the sea floor. PS10 is mainly deltaic.

Fig 49, 50: SB 2 is overlain by a rip-up clasts horizon (measured section locality Pa Co Chu Puk 3). Arrows point to individual rip-up clasts. The red line represents SB2. The hammer for scale in fig 49 is 25 cm. The scale in fig 50 is graded in cm.

The top of sequence 2 is bounded by SB3. The stacking pattern within sequence 2 is suggested to be aggradational but this interpretation is open because water depth of the lower-shoreface deposits (PS9) and delta front deposit (PS10) is hard to compare.

Sequence 3 is the youngest sequence within the Dakota Sandstone. It is 8 m thick and consists entirely of incised-valley-fill deposits (IVF2) (fig 51). The incised valley is defined based on the correlated measured sections (fig 41). Only one of the parasequences (PS11) within sequence 3 occurs within the Dakota Sandstone. The remaining parasequences are within the overlying Mancos Shale. Parasequence eleven contains one facies: high-energy fluvial channel, facies F. Locally, sequence boundary 3 is an erosional surface that truncates the upper part of PS 10 (delta front) of sequence 2. In other sections, where incision is not seen, SB3 is represented by its interfluve expression. The interfluve expression of SB3 is the boundary between the Dakota Sandstone and the overlying Mancos Shale (fig 52). In this case, sequence 3 lies entirely within the overlying Mancos Shale. Sequence 3 is only represented within the Dakota Sandstone by an incised-valley-fill (fig 53).

The fluctuations in sea level resulted in the two incised valley-fills (IVF1 and IVF2). Both valleys were formed in association with a period of relative fall in sea level causing erosion and regional truncation of strata by fluvial processes. IVF1 is characterized by a fluvial deposit which represents a lower energy system (facies E) than those of IVF2: IVF2 contains fluvial channel-fill deposit interpreted as more

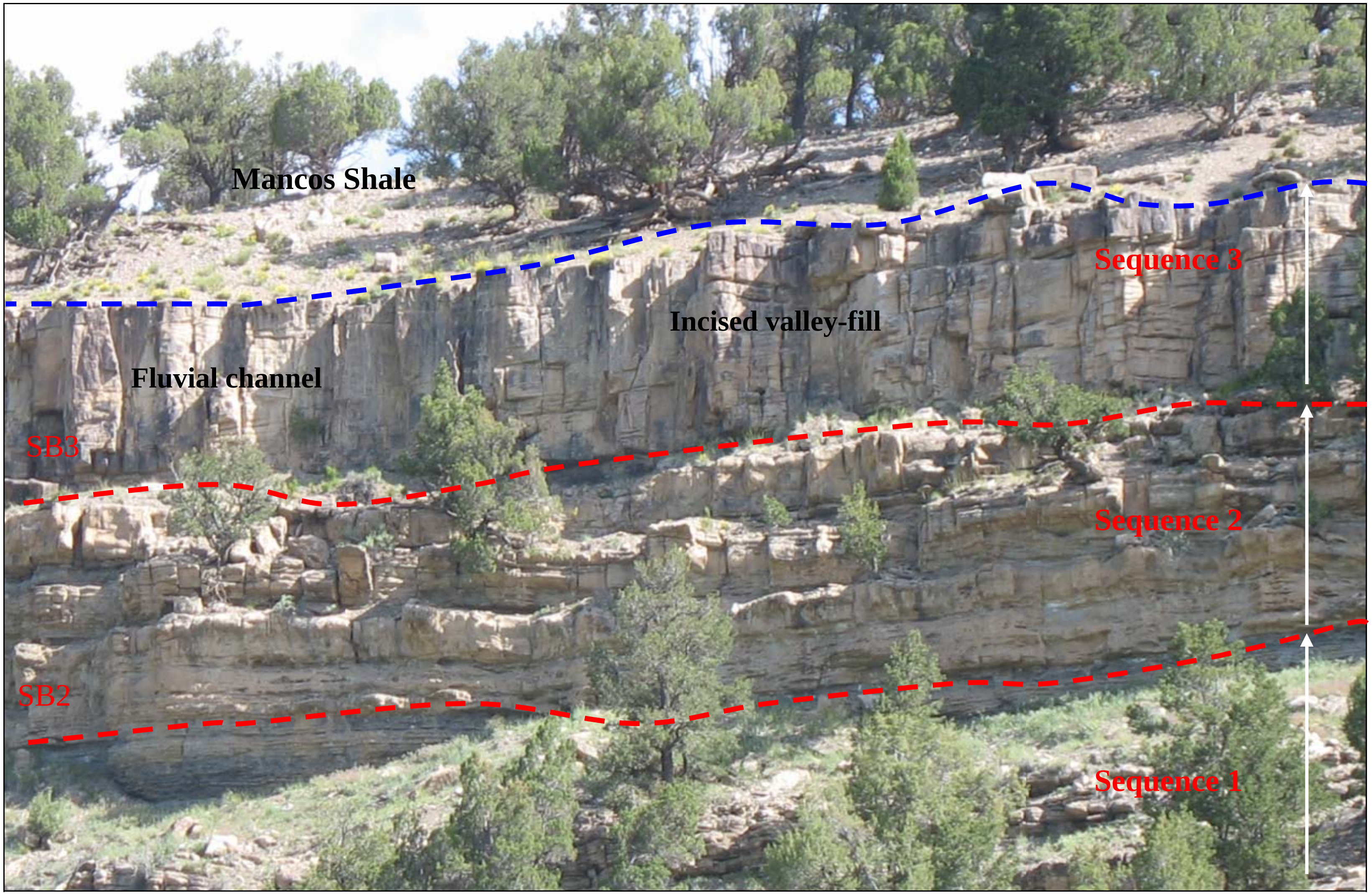

Fig 51: Photo mosaic of Dutch Charlie 2 measured section locality showing sequence 3 at the top of the Dakota Sandstone. This sequence contains one parasequence represented by fluvial channel.

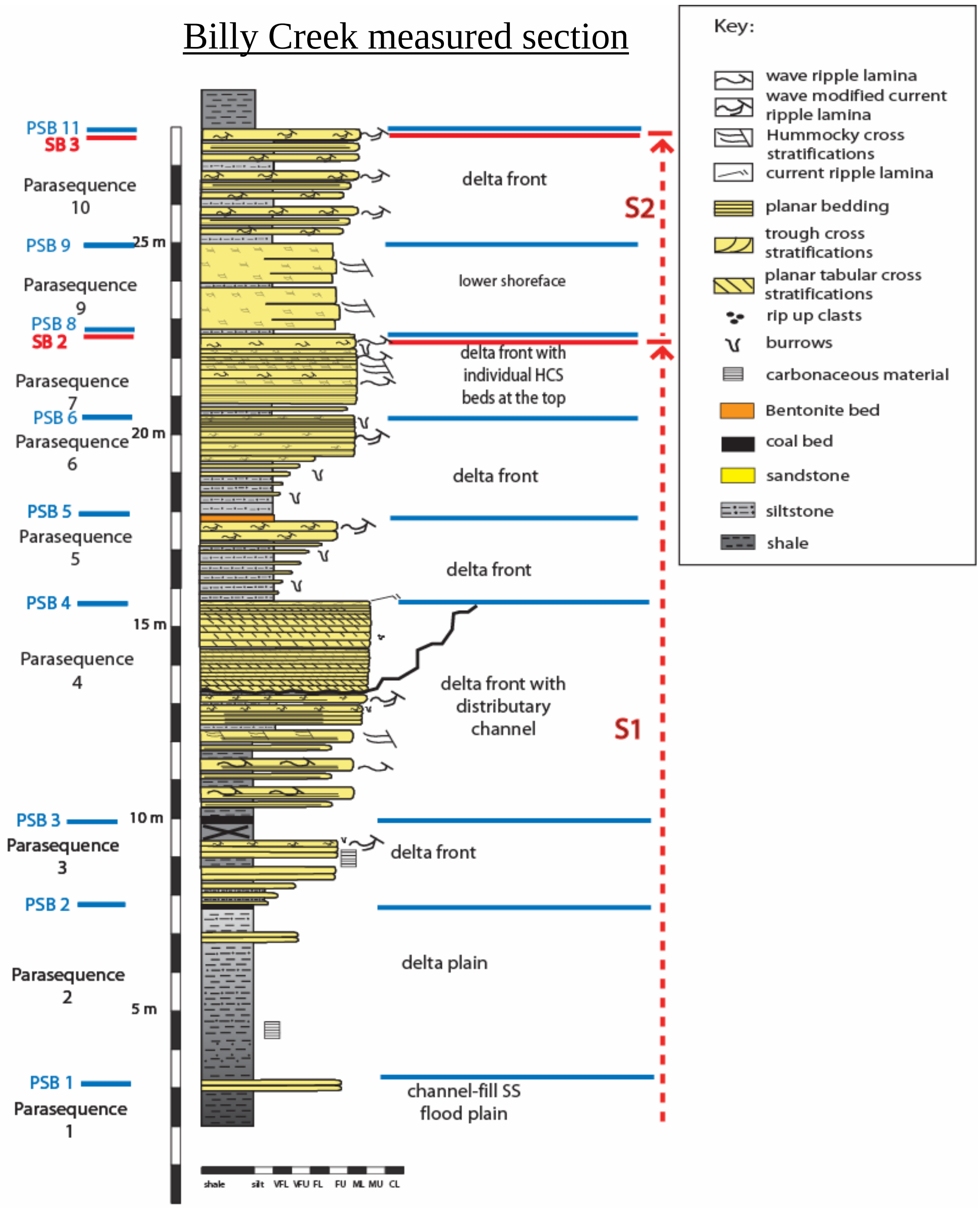

Fig 52: Schematic representation of Billy Creek measured section locality showing 9 parasequences and 2 sequences. PS 8 and 11 occur within incised valleys and are not present in the measured section. Sequence 3 is not present in this section. It is only represented by its interfluve expression surface. Blue lines represent a parasequence boundary, and red lines are sequence boundaries.

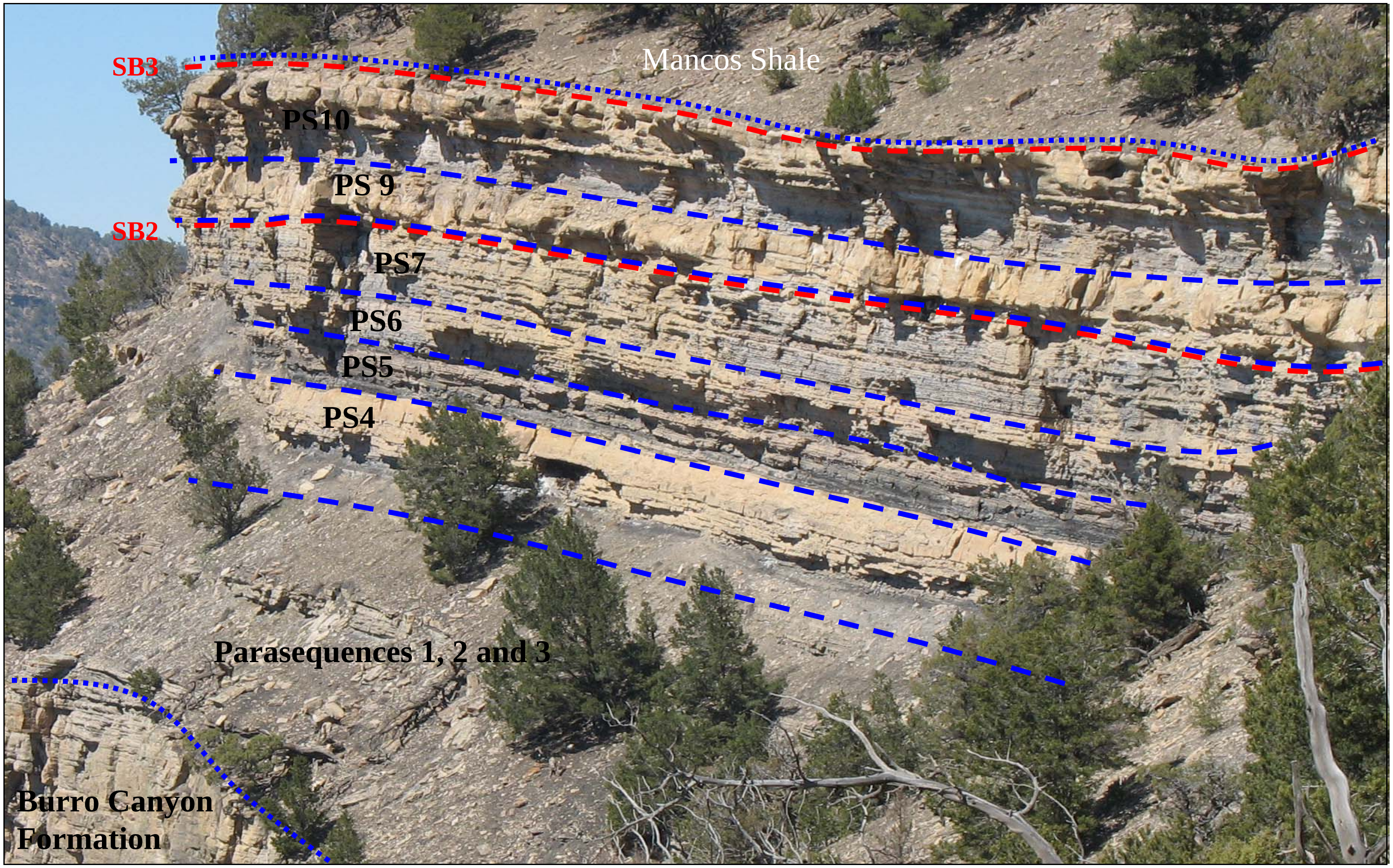

Fig 53: Panoramic picture of Chaffee Creek 1 measured section locality showing sequences 1 and 2. In this section, sequence 3 is not present. The base of S3 is represented by the interfluve expression of SB3, seen here as the Dakota Sandstone/ Mancos Shale contact.

braided (high-energy) in nature (facies F). The two incised-valley-fills within the Dakota Sandstone show other differences. Within the study area, IVF1 is thinner and more extensive than IVF2 (13 km Vs 5 km of mapped stratigraphic extent).

Incised-valley systems are filled during the late lowstand through the transgressive systems tracts (Zaitlin et al., 1994). In general, incised valleys contain complicated fills. The valley fill varies along depositional strike and also along depositional dip with respect to the shoreline. Zaitlin and others (1994) divided incised-valley-fills into three segments. From seaward to landward, these segments are as follows: segment 1 (outer), which is fully influenced by marine processes; segment 2 (middle), which is estuarine and segment 3 (inner), which is fluvial (fig 54). Zaitlin and others (1994) suggest that during the lowstand time, the mouth of the incised-valley is occupied by a delta. Up dip, the delta facies is replaced by a fluvial channel with a meandering pattern that passes up dip into a braided river system near the head of the incised valley (fig 55). The fill of the incised valley also changes vertically as the valley fills. Idealized valley fill contains high-energy fluvial deposit at the base, overlain by lower energy fluvial deposits with some tidal influence, which in turn are overlain by deposits with increasing tidal influence toward the top of the fill. During the transgressive systems tract time, the valley fills in a complicated manner (Zaitlin et al., 1994) (fig 54).

Two possible explanations are proposed to explain the stratal differences within the two incised-valley-fills of the Dakota Sandstone. The first explanation suggests that facies E and F represent different parts of an incised valley system.

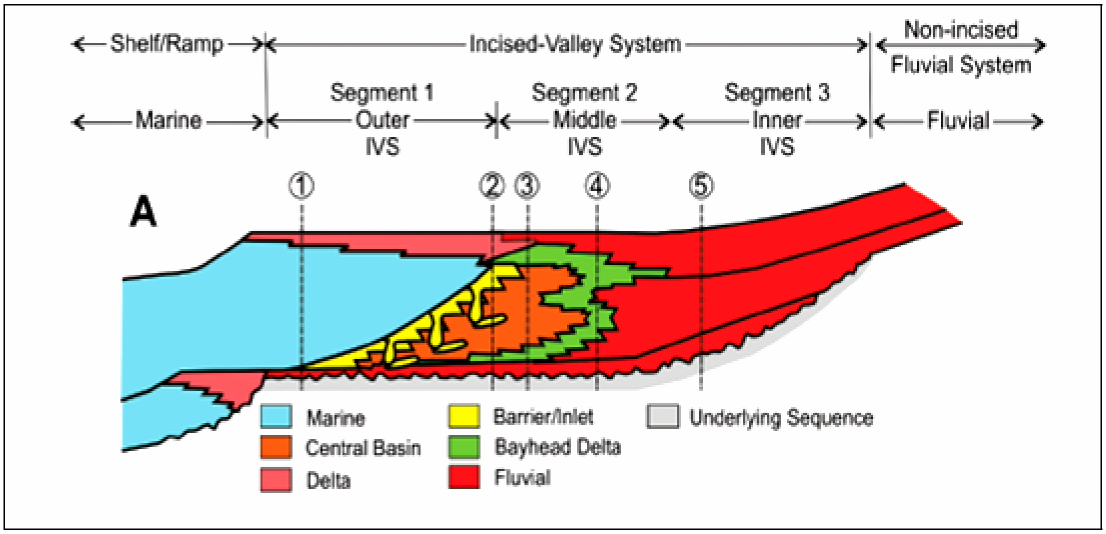

Fig 54: Idealized longitudinal section of a simple incised-valley-fill system showing the distribution of depositional environments (Zaitlin et al., 1994).

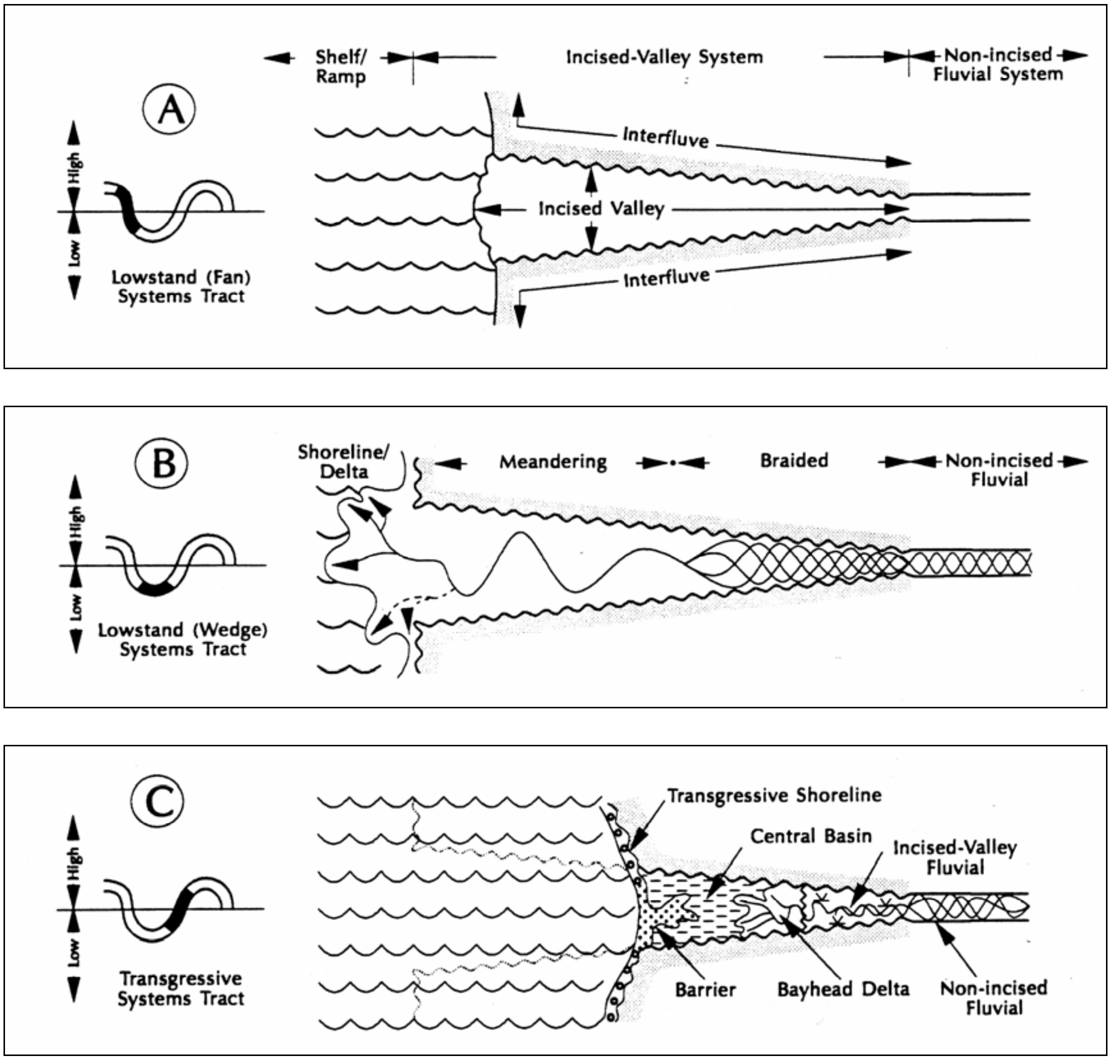

Fig 55: Plan view of an incised valley showing its evolution during sea-level change. (A) Lowstand time showing the incised valley system passing headward into a non-incised fluvial-channel system. (B) Lowstand (wedge) time showing a lowstand delta at the mouth of the incised valley, and the beginning of fluvial deposition throughout the incised valley system. (C) Transgressive systems tract time showing development of wave-dominated estuarine system within the incised valley (Zaitlin et al., 1994).

Facies F (high-energy environment, absence of upward-fining succession, absence of fine material, large bars of 90 cm think) is suggested to be located closer to the basal axis of a shallow incised valley. Facies E is interpreted as a low-energy environment (upward-fining succession, upward-thinning in bed thickness, and silt at the top) and is suggested to represent deposition on the flanks of the incised valley, where the energy of the channel started to decrease. The vertical facies trends proposed by Zaitlin and others (1994) (low energy fluvial channel, bay head delta, central basin and barrier) do not occur in the study area. The entire incised valley consists only of fluvial facies (facies F). The incised valley of sequence 2 may be a small valley, which was eroded and filled relatively quickly. Alternatively, IVF1 and IVF2 may represent deposition of different subenvironment (more proximal or more distal) within a similar type of valley. Facies F (high-energy fluvial channel) may represent deposition in the more proximal (inner) part of the IV, and Facies E may represent deposition in the more distal (outer) part of the IV.

Chapter IV: Depositional history and rate of transgression

I. Depositional history

The six facies identified within the Dakota Sandstone show continuous interaction between fluvial and marine processes during the initial transgression of the KWIS. Wave influence increases toward the top of the formation as seen by the deposition of HCS in the lower shoreface of PS 9, and the increase in the frequency, amplitude and thickness of wave ripples (from cm to dm) in the delta front facies of PS7. Brackish-water conditions are inferred from trace fossils. The trace fossils assemblage *Arenicolites, Diplocraterion, Skolithos* and *Planolites,* seen throughout the formation, is similar to one described as characteristic of brackish-water environments (Howard and Frey, 1975; Pemberton and Wightman, 1992; MacEachern and Pemberton, 1994; Gingras et al, 1999; and Pemberton et al, 2001). Within this assemblage, *Arenicolites* is the dominant trace fossil. *Arenicolites* is considered a good indicator of stressed conditions.

Throughout deposition of the Dakota Sandstone, the shoreline changed from a deltaic setting (parasequences 2-7), to a wave-dominated coastline (parasequence 9) and then back to a deltaic setting (parasequence 10). Parasequences 2 through 7 are composed of deltaic (delta front-distributary channel) deposits. Sedimentary structures within these facies record the interaction between current and wave processes with river processes dominating. Deltas formed in an embayed shoreline, where wave influence was limited. A change in shoreline configuration is proposed for the deposition associated with parasequence 9. The presence of thick HCS beds in PS 9 suggests a substantial increase in wave energy. The higher wave influence is interpreted to indicate a linear shoreline. This change in the shoreline configuration occurred after the fall in sea level which produced SB2. Delta-front deposits in PS10 are interpreted to indicate a return to an embayed shoreline setting. Similar changes in the shoreline configuration are documented in the Geologic Atlas of the Rocky Mountain Region (McGookey et al., 1972). The paleogeographic maps of Wyoming and Utah show a change from an embayed coastline setting during Turonian and Early Coniacian to a straight, linear shoreline during late Coniacian to Santonian time. This change in the shoreline configuration is similar to the one that occurred within the Dakota Sandstone, but at different time scale.

The deltaic setting interpreted for the study area is proposed to be composed of small-scale deltas. The deltas within the Ridgway area are considerably smaller in size than the deltaic lobes of the Mississippi Delta. Individual parasequences that consist entirely of deltaic sandstone, in both the transgressive and the highstand system tracts of the Mississippi delta, average 10 to 50 m thick (Penland et al, 1988). Parasequences of deltaic deposits within the Dakota Sandstone are approximately 4 m thick. The small size of the Dakota sandstone delta is also seen through its distributary channels. Throughout the Ridgway area, the distributary channels are small (averaging 3 m thick), and are similar to radial bifurcating channels described by Coleman and Prior (1981). The radial bifurcating channels and the small size of the deltas can explain the relatively quick lateral facies changes in the study area, which occur in a distance of 3 to 4 km. The deltas within the Dakota Sandstone are similar in size to those of the Wax Lake Outlet, Atchafalaya Bay, Louisiana. The entire Wax Lake Delta is less than 10 km wide. Subfacies (smaller deltaic lobes) average 2-3 km in width. Variation of facies within this delta occurs in a distance of about 3 to 4 km (fig 56). Its distributary channel shows a bifurcating pattern similar to the one within the Dakota Sandstone.

Fig 56: Subaerial picture of the Wax Lake Outlet Delta. This delta shows a nice bifurcating channel. The Dakota Sandstone is comparable in size to the Wax Lake Outlet Delta (Google Earth).

II. Rate of transgression

The initial transgression of the Cretaceous Western Interior Seaway across the Ridgway area was complicated. The presence of eleven parasequences and three sequences suggests that the transgression occurred in a series of steps. Following the deposition of the Burro Canyon Formation, a progressive rise in sea level resulted in the deposition of seven parasequences, which compose the lower half of the Dakota Sandstone. Following the deposition of PS7, a relative fall in sea level occurred, which coincided with regional erosion and formation of an incised valley (IV1). Deposition from a sinuous fluvial system within this incised valley (LST) occurred during the subsequent relative rise of sea level. Following the fill of the incised valley, thick HCS beds of a wave-dominated shoreline (PS9) were deposited. This was followed by the return of deltaic facies, seen with the deposition of PS10. Following the deposition of PS10, another fall in the sea level occurred and a second incised valley formed (IV2). Deposition within IV2 occurred during the subsequent rise. IV2 filled with high-energy fluvial deposits (PS11). This was the last stage of deposition of the Dakota Sandstone before the deposition of the overlying Mancos Shale.

The complicated sequence of events outlined above is seen in the complex parasequence stacking pattern within the Dakota sandstone. The mixture of retrogradational and aggradational stacking patterns separated by two sequence boundaries reflects these complexities.

Conclusion

Sequence-stratigraphic interpretation of the Dakota Sandstone in the Ridgway area indicates that the initial transgression of the Cretaceous Western Interior Seaway was complicated and occurred in different steps. Sedimentological study of the eleven measured sections reveals the presence of deltaic facies, lower shoreface and fluvial channel-fill facies. The deltaic facies predominate. They are represented by delta plain (facies A), delta front (facies B) and radial bifurcating distributary channel (facies C). These facies are part of river-dominated delta with limited wave influence. Lower-shoreface facies (facies D) is present in the upper part of the formation. The presence of HCS indicates high wave energy. This facies is overlain by another deltaic deposit. The increase in wave influence, seen through the transition from river-dominated delta, at the base of the formation, to lower shoreface succession and then back to another deltaic succession at the top of the formation, is interpreted to indicate a change in the shoreline configuration during the deposition of the Dakota Sandstone. The base of the formation was deposited initially as deltaic succession within an embayed coastline. Limited wave influence is seen in outcrop. The configuration of the shoreline changed toward the top of the formation. The presence of HCS within a shoreface setting indicates that the shoreline changed to a straight configuration in which wave influence is stronger. Deltaic facies at the top of the Dakota Sandstone shows the return to an embayed shoreline. The interaction between fluvial and marine processes continued through the Dakota Sandstone until the deposition of the Mancos Shale.

Deltaic facies within the Dakota Sandstone is comparable to the Wax Lake Outlet Delta, Louisiana. These two deltas share similar characteristics including size, radial bifurcating distributary channels and limited lateral extent. These features are seen in the Dakota Sandstone. Dakota distributary channel-fill are thin (~3 m) and extend laterally for approximately 100 m. Facies distribution within the same parasequence changes from delta front to distributary channel to delta plain in 3 to 4 km.

Sequence-stratigraphic interpretation of the Dakota Sandstone reveals the presence of three sequences with two incised-valley-fills and eleven parasequences. The first sequence starts in the Burro Canyon Formation and continues in the Dakota Sandstone. This sequence is bounded by SB2 (erosional surface and its interfluve expression) at its upper limit. Sequence one contains seven parasequences, including deltaic facies. These parasequences show a retrogradational followed by an aggradational stacking pattern. Sequence two is located entirely within the Dakota Sandstone. It is bounded by SB2 and SB3. The sequence boundaries are seen as both erosional and interfluve surfaces. Sequence two contains three parasequences, the lowest within an incised valley. The valley is filled with sinuous fluvial channel deposits, and is overlain by lower shoreface and delta front facies. PS8 and PS9 show a retrogradational stacking pattern. The stacking pattern in the upper part of the sequence (PS9 and PS10) is hard to identify but is suggested as aggradational. Sequence three starts in the Dakota Sandstone and continues into the overlying Mancos Shale. Within the Dakota Sandstone, sequence three consists entirely of high-energy fluvial channel deposits within an incised valley. The stacking pattern within this sequence is unidentified.

The study of the Dakota Sandstone in the Ridgway area indicates that the initial transgression of the KWIS was complicated. The initial transgression occurred in different steps including episodes of sea level rise and two relative falls in the sea level. The complexity is also seen through the stacking pattern. A simple, retrogradational stacking pattern is absent. Instead, the parasequence stacking pattern within the Dakota Sandstone is complex.

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